AAPM REPORT NO. 41

REMOTE AFTERLOADING TECHNOLOGY

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A REPORT OF AAPM TASK GROUP NO. 41
REMOTE AFTERLOADING TECHNOLOGY

Glenn P. Glasgow, Chairman
J. Daniel Bourland
Perry W. Grigsby
Jerome A. Meli
Keith A. Weaver

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The Charge to a Proposed Task Group on Remote Afterloading Systems

Remote afterloading of radioactive sources for brachytherapy is becoming increasingly popular in the United States as evidenced by the increased sales of remote afterloading systems. With low, medium, and high dose rate options, these units offer the potential for superior dose distributions and the practical advantages of better radiation protection. However, as with any new technology, these systems generate a host of new concerns that the users must address. This task group addresses several of these concerns.

Currently, there are no explicit protocols for source calibration. Often, calibration of these sources yields activities at odds with those provided by the manufacturers. This need for a dosimetry protocol is particularly important for the high activity ^{192}Ir sources which are exchanged frequently.

Remote afterloading systems present a unique set of radiation control questions, particularly when the units fail to function adequately and the sources stick in the applicators. The task group would suggest radiation control practices and quality assurance procedures for these systems.

Often existing hospital rooms or teletherapy vaults not originally designed for the remote afterloading systems are used to house these units. Certain pitfalls in such uses will be described and precautions will be suggested. Methods for the design of facilities specifically for these systems will be outlined.

A review of currently available computation methods for dose calculations and optimization will be presented.

The specific charge to this task group is:

1. To review the principles of operation of the commercially available remote afterloading systems.

2. To recommend a procedure for the calibration of the strength of the sources employed in these systems.

3. To suggest radiation control practices, with special emphasis on emergency response procedures.

4. To recommend quality assurance procedures for an efficacious use of these systems.

5. To outline special considerations that must be addressed in the design of a facility for the use of remote afterloaders.

6. To review the currently available methods for dose computation and optimization for treatment planning.

Ravinder Nath, Chairman
Radiation Therapy Committee
December 20, 1988

FOREWORD

The most difficult task of Task Group 41 was to review methods of calibrations of high activity (370.-GBq [10.0-Ci]) ^{192}Ir sources used in high dose rate remote afterloading units and to recommend a calibration protocol for these sources. While there have been significant developments in obtaining ^{192}Ir calibration factors for thimble ionization chambers used for secondary standards (relative to National Institute of Standards and Technology primary standards) and for re-entrant well ionization chambers used as tertiary standards, we still lack a NIST primary standard for thimble ionization chambers irradiated with ^{192}Ir. Moreover, participants of a recent NISI' workshop, The Calibration of Iridium-192 Sources for Use in High-Dose-Rate (HDR) Brachytherapy, indicated development of a primary standard is unlikely in the immediate future.

The Task Group 41 final report does explain the recently adopted AAPM-approved ADCL procedure for obtaining an N_x factor for ^{192}Ir for thimble chambers by interpolation between other N_x factors for energies bounding ^{192}Ir, explains how this factor is transferred to re-entrant well ionization chambers, and advises AAPM members on the use of re-entrant well ionization chambers for measuring source activity.

Finally, significant developments in methods of ^{192}Ir source calibrations that may have occured while this manuscript was in press obviously are excluded. Nevertheless, we trust this report will serve as a useful resource for the members of the American Association of Physicists in Medicine and others.

Glenn P. Glasgow, Chairman, TG 41
March 2, 1993

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ABSTRACT

Remote afterloading of low dose rate (LDR), medium dose rate (MDR), and high dose rate (HDR) radioactive materials for brachytherapy is increasingly practiced in the United States. This report presents the advantages and disadvantages of the units, lists some commercial remote afterloaders and their features, and reviews facility requirements, radiological safety, licensing and license compliance, calibration methods, acceptance testing, quality assurance, and isodose computation.

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I. INTRODUCTION

Remote afterloading of radioactive materials for brachytherapy is increasingly practiced in the United States. The earliest remote afterloading devices, developed in the early 1960's, were refined and used for brachytherapy in England, Europe, and at a few facilities in the United States.' Originally, there were only a few manufacturers of these devices. Several current manufacturers offer devices with many diverse features. A review of proceedings of the meetings[2-7] sponsored by the device manufacturers reveals that radiation oncologists are using remote afterloading brachytherapy in numerous anatomic sites.

A. Advantages of Remote Afterloading

Remote afterloading improves radiation control and provides technical advantages, such as isodose distribution optimization, that improve patient care. Replacing manual afterloading with remote afterloading reduces the radiation exposure to radiation oncologists, physicists, attending physicians, source curators, nurses, and other allied health personnel.[8,9]

Remote afterloading is an application of the *As Low As Reasonably Achievable* (ALARA) principle in radiation control. The decision by the United States Nuclear Regulatory Commission to adopt ALARA as a license requirement for by-product materials licenses, rather than as a voluntary committment, is a motivating factor for purchasing remote afterloading units.[10] Remote afterloading offers less probability of temporarily misplacing radioactive sources or actually losing sources, events that do occur with manual afterloading."

Nurses caring for patients treated with an LDR unit, one in which conventional doses of about 10-Gy are delivered daily for several days, can retract radioactive sources as required to provide more nursing care with less fear of radiation exposure." An LDR unit in a dedicated room eliminates the undesirable practice of assigning patients to different rooms in the hospital so that one group of nurses will not care for all implant patients, With a dedicated room

containing an LDR unit, a single nursing staff unit can be better trained, and patients generally receive better care. For the Radiation Safety Officer, there are distinct regulatory and procedural advantages from having a single group of nurses for whom training records and personnel exposure records must be maintained and for whom initial, continuing and annual instructions in radiation safety must be given.

High dose rate remote afterloading devices yield dose rates greater than 0.2-Gy/min; doses of several gray generally are delivered in minutes, High dose rate remote afterloading is particularly appealing to facilities with large patient populations; they, if treated by conventional manual LDR brachytherapy, would require prolonged hospitalizations. Treating these patients as outpatients, using multiple fraction treatment regimens on a remote HDR device, is appealing to the patients, Free standing radiation therapy centers that do not provide hospital rooms find HDR units appealing. A dedicated HDR treatment suite with an overhead x-ray tube and fluoroscopy can accommodate many patients yearly; large workloads are possible on a single unit. There is little radiation exposure to attending medical personnel and none to adjacent patients; adjacent patients receive radiation exposure with manual LDR or remote LDR afterloading. Applicators can be rigidly secured for the short treatment times common with HDR therapy; consequently, undesired applicator movement observed during prolonged hospital stays required with LDR brachytherapy is reduced.[13] In some instances, the HDR remote afterloading sources can be configured more advantageously, yielding more desirable dose distributions than those achieved with conventional LDR radioactive sources and manual afterloading. In treatments of some gynecologic cancers with HDR units, urinary catheters are not required, as with conventional treatments. Vaginal packing requirements often are less. Hence, HDR therapy is an appealing alternative to LDR therapy in treating gynecologic malignancies.[14,15,16]

Finally, the very small diameter (about l-mm) high activity 148.0-GBq (4.0-Ci) to 740.0-GBq (20.0-Ci) ^{192}Ir sources in HDR remote afterloading units allow treatments of interstitial and intraluminal sites (esophagus, bronchus, bile duct, brain, etc.) previously untreated or

treated only with difficulty with conventional LDR manual afterloading techniques.[17]

Medium dose rates are those between low and high dose rates; several 10-Gy doses can be delivered in several hours. Interest in MDR remote brachytherapy is less pronounced than interest in HDR remote brachytherapy.

B. Disadvantages of Remote Afterloaders

Remote afterloaders are not free of disadvantages. The devices require a modest capital expenditure of $150,000 to $300,000, and the cost of renovating a conventional hospital room to accommodate an LDR unit is probably $50,000 to $100,000. An HDR suite is more costly, a dedicated HDR room and ancillary x-ray imaging equipment will likely cost $200,000 to $500,000.

Locating an HDR device in a shielded radiotherapy vault with external beam equipment used daily eliminates the cost of building a dedicated room or renovating an existing room, but limits the availabiity of the HDR device and teletherapy unit and complicates patient scheduling. Moreover, the radiotherapy vault may not accommodate desired x-ray imaging equipment required for source localization.

Patient misadministrations still can occur because of operator error in programming or entering incorrect treatment parameters.[18,19] Radiation emergencies still occur. Source guide tubes can detach from the machines or patients;[20] LDR and HDR sources can become lodged in the source guide tubes. Unshielded HDR sources offer potentially higher inadvertent radiation exposure to personnel than unshielded LDR sources[21] Extensive routine and emergency radiation control procedures must be developed to ensure proper use and control of LDR, MDR and HDR sources.

Finally, relative to conventional manual LDR methods, for either LDR or HDR remote afterloading brachytherapy, the historical data bases of five year survival rates and early and late tissue complication rates by anatomic site are not as extensive. Numerous treatment regimens and fractionation schema are used in HDR brachytherapy. The number of fractions and doses to provide treatment results equivalent to those obtained with conventional LDR brachytherapy is under active investigation. Although this topic is beyond the scope of this report, there are numerous literature articles to which the reader may refer.[22] [33] However, the advantages of remote afterloading therapy appear to outweigh the disadvantages and sales of remote afterloading units are increasing.

II. FEATURES OF REMOTE AFTERLOADING SYSTEMS

A. Essential Features

All remote afterloaders offer four essential features:

1. A primary storage safe to contain the sources(s) when not in use.

2. A mechanism to move the source(s) from the storage safe to and from applicator(s) in the patient.

3. A system to maintain the source(s) in the applicator(s) for a set time in desired positions and to determine their position(s).

4. A mechanism to return the source(s) to the storage safe at the end of treatment and during power failures or other emergencies.

B. Radioactive Sources

The radioactive nuclides used in remote afterloading are ^{60}Co, ^{137}Cs, and ^{192}Ir. The first two offer longer half-lives but lower specific activities than achieved with ^{192}Ir. Hence, ^{60}Co and ^{137}Cs sources are used in LDR, MDR, or HDR devices designed for intracavitary

treatment with applicators that have larger inner lumens that accommodate the larger diameter (3-to 4-mm) ^{60}Co and ^{137}Cs sources.

Higher activity ^{192}Ir sources with smaller diameters (about l-mm) are best for intraluminal HDR treatments. However, the 73.8-d half-life of ^{192}Ir necessitates three to four source changes yearly at an annual cost of $8,000 to $15,000.

C. Compendium Contents

Tables I and II compare features of commercially available remote afterloaders. These data represent the authors' understanding of features of each unit based on personal use and representations made in commercial and technical sales literature. The purpose of the compendium is not to identify the best or most desirable products; rather, it compares the features of the units to allow those unacquainted with this technology to better understand these features. Remote afterloading is a rapidly developing field and new features may well have been added to these units by the manufacturers prior to the publication of this report. Twenty items are identified and included in the compendium:

1. Dose Rate. ICRU Report 38[34] notes that "low" denotes conventional dose rates where the prescribed dose rate at the point of dose prescription is between 0.40-Gy/h (0.0067-Gy/min) to 2.0-Gy/h (0.033-Gy/min); "medium" denotes dose rates greater than 2.0-Gy/h (0.033-Gy/min) and less than 12.0-Gy/h (0.20-Gy/min); and "high" denotes dose rates greater than 12.0-Gy/h (0.20-Gy/min).[34] "Pulsed remote afterloading, under active development, uses up to a 37.-GBq (1.0-Ci) ^{192}Ir source for 10- to 30-minutes, yielding instantaneous dose rates of 1.0-Gy/h (0.017-Gy/min) to 3.0-Gy/h (0.05-Gy/min)[35]

2. Modality. Intraluminal denotes irradiation by small radioactive sources inserted into small lumens (esophagus, bronchus, bile duct, etc.), while intracavitary and interstitial retain their historical meaning. Intraoperative denotes irradiation during surgical operations,

3. Outside Diameters of Intracavitary, Intraluminal, and Interstitial Applicators. Self-explanatory, but important as the applicators' outside diameters are the limiting factor for treating certain anatomic sites.

4. Method of Source Transfer (to the patient from projector or device). Methods include ball chains, drive cables, helical steel springs, and pneumatic techniques.

5. Method of Movement. Methods include oscillating cams, stepping drive motors, and use of active/inactive pellets to achieve desired source configurations and dose distributions.

6. Source Retraction in Event of Failure. If power fails, how will sources be removed from the patient? Falling weights, back-up batteries, and hand cranks all are used.

7. Source Storage. Where are sources stored? Is there any additional storage device other than the treatment unit? Does the unit have a second or supplemental storage unit?

8. Simulation Sources for Treatment Simulation. Are inactive sources available that allow simulation of the planned therapy?

9. Applicators Available. Self-explanatory, and dependent on source design.

10. Accuracy of Source Positioning. How accurately will the unit position an individual source or source array in a patient? The generally accepted standard of positional accuracy is l-mm.

11. Source Arrangements, How are different source arrays achieved? Methods included oscillating one or more sources, pre-loaded source trains (pencils), active and inactive pellets that can be interchanged, and stepping sources.

12. Uses Conventional RTP (Radiotherapy Treatment Planning) Software for Dosimetry? How are isodose distributions obtained? Can one use a commercial RTP computer for isodose computations or must other dedicated computers or other techniques (preplanned isodose atlas) be employed?

13. Dose Optimization Available. Is there dose optimization software available with the device?

14. Bladder and Rectal Dosimetry. Does the unit offer a method of measuring these doses? Some devices offer low activity pilot or test sources designed for such dosimetry.

15. Source Container Maximum Storage Activity. What maximum activity in megabecquerels (curies), of ^{137}Cs, ^{60}Co, or ^{192}Ir can be stored in the unit? In any secondary storage unit?

16. Special Features. What is unique about the unit?

17. Number of Applicator Channels, How many channels does the unit have?

18. Maximum Number of Sources in Device. How many different radioactive sources can be stored in the unit at one time?

19. Maximum Number of Channels Used Simultaneously. How many of the available channels can be used at the same time?

20. Sources Available. Which radioisotopes are available? What is their physical form, size, and individual source activities?

Other parameters not included in Tables I and II, but that are features of some units, include:

a. Memory for Standard Treatment Positions. Can selected treatments be stored in memory for future treatments to be performed

at a later date (e.g., for a repeat treatment of the same source configuration required with fractionated therapy or for use on a series of patients requiring the same treatments)?

b. Safety Features. How are applicator connections checked? Is there a back-up timer of any type? How is the source position confirmed?

c. Dummy Runs To Check Applicators Prior to Treatment. Can the unit mechanically or electronically check applicator connections and insure the right combination of applicators and source guide tubes before treatment commences?

D. Remote Afterloading Devices

Table 1 lists six remote afterloading devices with low or medium dose rate features, one high dose rate device, and one pulsed dose rate device. The Afterloading Buchler unit (now marketed by STS Steuerungstechnik-Strahlenschutz GmbH) features an oscillating cam that moves a single source over 20-cm length to produce variable radiation distributions. For treatment of gynecologic cancers, two stationary sources are used as colpostat sources with the oscillating cam moving the tandem source to provide a 3-channel system. This unit has an option for interchange between LDR and HDR operating modes if the user has purchased suitable LDR and HDR sources.

The Curietron has four channels and is available as a low, medium, or high dose rate unit. The source safe contains ^{137}Cs sources 1.8-mm in external diameter by 5.3-mm in length and inactive spacers that arc loaded to form sources of the desired active lengths. The device contains the storage safe for the sources, the electromechanical transfer system, and the operating control panel. Sources with activities varying from 555.-MBq (15.0-mCi) to 5.55-GBq (150-mCi) with active length of 8-mm to 96-mm can be formed. Conventional metallic applicators of either the Fletcher or Henschke design are available, as are plastic applicators of the DeLouche or Chassagne type popular in Europe. The high dose rate projector can contain up to 185.-GBq (5.0-Ci) of ^{137}CS.

Table 1 (a) - Low, Medium, and High Dose Rate Remote Afterloading Devices

Manufacturer, or Vendor	Afterloading BUCHLER Buchler GmbH Germany	Curietron Oris (CIS-US) France	MicroSelectron (LDR) Nucletron Engineering BV Netherlands	Selectron (LDR) Nucletron Engineering BV
1. Dose Rates	Low, Medium, High	Low, Medium, High	Low	Low, Medium
2. Modality	Intracavitary Intraluminal Interstitial	Intracavitary	Intraluminal Interstitial	Intracavitary
3. Outside Diameter of Applicators	^{137}Cs: 8- to 6-mm ^{60}Co: 8-, 4-,3.15-, 2.2-mm ^{192}Ir: 6-, 5-, 4-, 3.15- and 2.2-mm	^{137}Cs: 4.2- to 3.2-mm	^{192}Ir: 1.5-mm ^{137}Cs: 1.9-mm	^{137}Cs: 6-mm
4. Method of Source Transfer	Sources mechanically auto connect to ball chain	Sources auto connect to drive cable	Sources auto connect to drive cable; monitored by microprocessor	Pneumatic microprocessor controlled)
5. Method of Source Movement	Oscillating cam moves one source over 20-cm; two sources remain fixed	None; static	Stationary linear sources or seed arrays	Source Trains with 48 pellets/120-mm; any pellet may be programmed to be active/inactive
6. Method of Source Retraction in the Event of a Failure	Gravity (falling weight)	Backup battery and safety device	Back-up battery	Emergency battery to operate air reservoir for pneumatic return
7. Storage of Source	3 in unit and 3 in source changing container	10 or 20 preloaded trains in mobile safe	15 in unit; 45 in mobile safe	All in unit
8. Simulation Sources for Treatment Simulation	No	No	Manual	Manual or 1-mCi Co source, available option
9. Applicators Available	Munich; Paris; Bejing; Manchester; Stockholm; Rome; Fletcher; Interstitial	Delouche, Chassagne, Fletcher, Henschke	Interstitial applicators either rigid or flexible bronchial, esophageal	> 60 types
10. Accuracy of Source Position	Not stated in commercial literature	Not stated in commercial literature	1-mm, pneumatic check	± 1-mm with pneumatic check
11. Source Arrangements and Dose Calculation	Cam oscillates tandem source and two stationary sources to yield preselected (Atlas) distribution	Preloaded sources arranged to give desired distribution. Conventional arrangements	Linear or point interstitial sources arranged by user	Point sources individually constructed to yield any desired distribution
12. Uses Conventional RTP Software or Dosimetry?	No; uses isodose atlas	Yes, using point source programs; isodose atlas	Yes, or uses dedicated IBM-PC	Yes, has dedicated IBM-PC and software; however, conventional RTP point source programs could be used
13. Dose Optimization Table	No	No	No	Visual inspection of isodose distribution
14. Bladder and Rectal Dosimetry	Treatment terminates at present dose on detectors used during treatment	Option	No	Measured doses using pilot sources

Table 1 (a) (Cont'd.) - Low, Medium, and High Dose Rate Remote Afterloading Devices

Manufacturer, or Vendor	Afterloading BUCHLER Buchler GmbH Germany	Curietron Oris (CIS-US) France	MicroSelectron (LDR) Nucletron Engineering BV Netherlands	Selectron (LDR) Nucletron Engineering BV
1 Dose Rates	Low, Medium, High	Low, Medium, High	Low	Low, Medium
2 Modality	Intracavitary Intraluminal Interstitial	Intracavitary	Intraluminal Interstitial	Intracavitary
15. Source Container Maximum Storage Activity	^{137}Cs: 12-Ci ^{60}Co: 1.2-Ci ^{192}Ir: 10-Ci	^{137}Cs: 5-Ci (HDR)	Intermediate Safe ^{137}Cs: 1-Ci ^{192}Ir: 5-Ci Mobile Safe ^{137}Cs: 3-Ci ^{192}Ir: 15-Ci	^{137}Cs: 2.2-Ci
16 Special Features	Options for interchange between LDR & HDR modes	Checks and confirms microprocessor	None	Pneumatic checks of source positions
17. Number of Applicator Channels	1 or 3	4	15	3 or 6
18 Maximum Number of Sources in Projector	3	10 or 20	45 wires or ribbons	48
19 Maximum Number of Channels Used Simultaneously	1 oscillating 2 stationary	4	15	3 or 6
20 SOURCES AVAILABLE:				
a. Radioisotope	^{137}Cs	^{137}Cs	^{137}Cs	^{137}Cs
Physical Size	Capsule, 11.5-mm L × 6.5-mm OD	Capsules in train, 20.3-mm × 2.65-mm OD	Mini seeds up to 140-mm L × 0.8-mm OD in 1.3-mm OD train	Pellets 2.5-mm
	4-Ci	500- or 1000-mCi	5-mCi/seed	10 to 40-mCi per pellet
b. Radioisotope	^{60}Co		^{192}Ir	
Physical Size	Capsule not stated		Ribbons (wire, seed) up to 140-mm L x 1.1-mm OD	
Activity	1.2-mCi		(selected by user)	
c. Radioisotope	^{192}Ir			
Physical Size	Capsule, 2.4-mm L × 4-mm OD			
Activity	5- to 10-Ci			

Table 1 (b) - Low, Medium, and High Dose Rate Remote Afterloading Devices

Manufacturer, or Vendor	MINIRAD Isotopen-Technik Dr. Sauerwein GmbH Germany	Inter-Pal Inter-Pal-GmbH Germany	OMNITRON-2000 OMNITRON Corporation USA	MicroSelectron (PDR) Nucletron Corporation USA
1. Dose Rates	Low	Low	High	Low/Medium (variable)
2. Modality	Interstitial	Intracavitary Interstitial Intraluminal	Intraluminal Interstitial Intracavitary	Intraluminal Interstitial Intracavitary
3. Outside Diameter of Applicators	1.6-mm to 8-mm	4-mm	Smallest: 20-guage (0.89-mm needles)	^{192}Ir-1.4-mm
4. Method of Source Transfer	Some magnetically connect to drive cables	Sources mechanically connect to drive cables	Source permanently connected to stainless steel cable	Source laser welded to drive cable
5. Method of Source Movement	None; static	None, static	Steps source in 11-mm increments over 1.5-m	Stepping motor 48 steps of 2.5-mm over 12-cm length 48 steps of 5.0-mm over 24-cm length
6. Method of Source Retraction in the Event of a Failure	No	Back up battery	Back up battery; mechanical crank	Dual monitors and backup battery Emergency hand crank
7. Storage of Source	16 in unit; 16 in containers	30 in unit;	In unit; up to 12-Ci	1.0-Ci source ^{192}Ir
8. Simulation Sources for Treatment Simulation	No	No	Yes	Yes
9. Applicators Available	Conventional interstitial needles; Heyman applicators	Conventional interstitial needles	Interstitial needles; numerous catheters	Flexible & rigid needles bronchial, esophagus intracavitary (> 150)
10. Accuracy of Source Position	Not stated in commercial literature	Not stated in commercial literature	± 1-mm	± 1-mm
11. Source Arrangements and Dose Calculation	Use preloaded seeds in ribbons to give desired distribution	Use preloaded seeds in ribbons to give desired distribution	Steps/dwell times used to achieve desired dose distribution	Point source at 48 positions; 2.5-mm apart or 5-mm apart. 999 seconds in 0.1 second increments. Pulsed variable 10 minutes up to 4 hours
12. Uses Conventional RTP Software or Dosimetry?	Yes; has dedicated RTP software	Yes	Features dedicated RTP system	Yes or dedicated planning systems
13. Dose Optimization Table	Not stated	No	Yes	Yes: 300 optimization points
14. Bladder and Rectal Dosimetry	No	No	No	Yes

Table 1 (b) (Cont'd.) - Low, Medium, and High Dose Rate Remote Afterloading Devices

Manufacturer, or Vendor	MINIRAD Isotopen-Technik Dr. Sauerwein GmbH Germany	Inter-Pal Inter-Pal-GmbH Germany	OMNITRON-2000 OMNITRON Corporation USA	MicroSelectron (PDR) Nucletron Corporation USA
1. Dose Rates	Low	Low	High	Low/Medium (variable)
2. Modality	Interstitial	Intracavitary Interstitial Intraluminal	Intraluminal Interstitial Intracavitary	Intraluminal Interstitial Intracavitary
15. Source Container Maximum Storage Activity	Not stated	Not Stated	^{192}Ir; 12-Ci	^{192}Ir 2 Ci
16. Special Features	Allows sequential loading of several patients	Infrared remote controller for source transfers	Small source size; allows use of small interstitial needles	Memory storage of 100 channels and memory card
17. Number of Applicator Channels	16	30	10	18
18. Maximum Number of Sources in Projector	16	30	1	1
19. Maximum Number of Channels Used Simultaneously	16	30	1	1
20. SOURCES				
a. Radioisotope	^{192}Ir	^{192}Ir	^{192}Ir	^{192}Ir
Physical Size	Seeds in ribbons, dimensions unspecified	Ribbons 0.7- to 3-mm OD, length unspecified Conventional activities	Capsule 0.59-mm OD × 10-mm L 12-Ci max	2.5-mm capsule (length) 1.1-mm diameter 0.5 to 1-Ci
b. Radiosotope Physical Size Activity				
c. Radioisotope Physical Size Activity				

Table 2 (a) - High Dose Rate Remote Afterloading Devices

Manufacturer or Vendor	Afterloading BUCHLER Facts Buchler GmbH & Co. (Germany)	Curietron Oris (CIS-US) (France)	Curietron-192 Oris (CIS-US) (France)	MicroSelectron (HDR) Nucletron Engineering BV (Netherlands)
1. Dose Rates	High	High	High	High
2. Modality	Intracavitary Intraluminal Interstitial	Intracavitary	Intracavitary Interstitial	Intraluminal Interstitial Intracavitary
3. Outside Diameter of Applicators	5-mm to 1.7-mm	^{137}Cs: 4.2 to 3.2-mm	- - - - - - - - - - - - - -	^{192}Ir: 1.4-mm
4. Method of Source Transfer	Sources welded to steel drive cable	Sources auto connect to drive cable	Sources welded to steel drive cables	Source laser welded to drive cable
5. Method of Source Movement	Stepping motor; 60 steps to 300-mm length	None; static	Shifting mechanism; 32-steps over 640-mm	Stepping motor; 48-steps of 2.5-mm over 12-cm length; 5-mm over 24-cm; 48-steps
6. Method of Source Retraction in the Event of Failure	Emergency motor; backup battery	Backup battery and safety device	Backup battery	Dual monitors and backup battery; emergency hand crank
7. Storage of Source	1; 10-Ci	10 or 20 preloaded trains in mobile safe	1 source; 10-Ci	1; 10-Ci
8. Simulation Sources for Treatment Simulation	Yes	No	Yes	Dummy Source
9. Applicators Available	All applicators on the market are usable	Delouche, Chassagne, Fletcher, Henschke	Same as Curietron; plus interstitial (14 guage)	Flexible and rigid needles, bronchial; esophagus, intra-cavitary of many types
10. Accuracy of Source Position	± 1-mm	Not stated in commercial literature	± 1-mm	± 1-mm
11. Source Arrangements and Dose Calculations	Stepping source and variable dwell times	Pre-loaded sources arranged to give desired distribution. Conventional arrangements	Shifting mechanisms move sources to selected positions	Point source at 48-positions, 2.5-mm apart, dwell times to 999 seconds in 0.1 second increments

Table 2 (a) (Cont'd.) - High Dose Rate Remote Afterloading Devices

Manufacturer or Vendor	Afterloading BUCHLER Facts Buchler GmbH & Co. (Germany)	Curietron Oris (CIS-US) (France)	Curietron-192 Oris (CIS-US) (France)	MicroSelectron (HDR) Nucletron Engineering BV (Netherlands)
1. Dose Rates	High	High	High	High
2. Modality	Intracavitary Intraluminal Interstitial	Intracavitary	Intracavitary Interstitial	Intraluminal Interstitial Intracavitary
12. Uses Conventional RTP Software for Dosimetry?	Yes, has IBM-PC and software	Yes, using point source programs; isodose atlas	Yes, using point source program isodose atlas	Yes, or uses dedicated IBM-PC
13 Dose Optimization Available?	Yes	No	Yes	Yes; 40 optimization points
14 Bladder and Rectal Dosimetry	Yes	Option	Yes	No
15. Source Container Maximum Storage Activity	^{192}Ir: 10-Ci	^{137}Cs: 5-Ci (HDR)	^{192}Ir: 2 × 10-Ci	^{192}Ir: 10-Ci
16. Special Features	Memory storage of all planned and treated patients	Checks and confirms microprocessor	Checks and confirms microprocessor	Memory storage of prior treatments, multiple fractions
17. Number of Applicator Channels	12	4	20	18
18. Maximum Number of Sources in Projector	1	10 or 20	1	1
19. Maximum Number of Channels Used Simultaneously	1	4	2	1
20. SOURCES AVAILABLE:				
a. Radioisotope Physical Size	^{192}Ir 4.1-mm L × 1.6-mm OD 10-Ci 7.5-mm L × 1.1 D 10-Ci	^{137}Cs Capsules in train 20.3-mm × 2.65-mm OD 500- or 1000-mCi	^{192}Ir Capsule 1.2-mm OD × 14-mm 12-Ci	^{192}Ir Capsule 4.5-mm L × 1.1-mm OD 10-Ci

Table 2 (b) - High Dose Rate Remote Afterloading Devices

Manufacturer or Vendor	Selectron (HDR) Nucletron Engineering BV (Netherlands)	Gamma Med II ISOTOPEN-TECHNIK Dr. Sauerwein GmbH & Co. (Germany)	Gamma Med IIi ISOTOPEN-TECHNIK Dr. Sauerwein GmbH & Co. (Germany)	Gamma Med 12i ISOTOPEN-TECHNIK Dr. Sauerwein GmbH & Co. (Germany)
1. Dose Rates	High	High	High	High
2. Modality	Intracavitary Intraluminal Intracavitary	Intracavitary Intraluminal	Intracavitary Interstitial Intraluminal	Intracavitary Interstitial Intraluminal
3. Outside Diameter of Applicators	^{60}Co: 6-mm	3-mm to 8-mm	1.6-mm to 8-mm	1.6-mm to 8-mm
4. Method of Source Transfer	Pneumatic (microprocessor controlled)	Source electron beam welded to steel drive cable	Source electron beam welded to steel drive cable	Source electron beam welded to steel drive cable
5. Method of Source Movement	Source trains with 48-pellets over 120-mm; any pellet may be programmed to be active/inactive	Stepping motor; 20-steps to 200-mm length	Stepping motor; 20-steps; 200-mm max; also 1-mm steps	Stepping motor; 40-steps to 400-mm length; 1-mm to 10-mm steps
6. Method of Source Retraction in the Event of Failure	Emergency battery to operate reservoir for penumatic return or gravity	Hand crank, backup battery	Hand crank, backup battery	Hand crank, backup battery
7. Storage of Source	All in unit; 10-Ci max	20-Ci max	1; 10-Ci	1; 10-Ci
8. Simulation Sources for Treatment Simulation	Dummy Source	No	No	Dummy Source
9. Applicators Available	> 60, available	Fletcher, Manchester, vaginal (shielded) rectal(shielded) numerous intraluminal catheters	Fletcher, Manchester, vaginal (shielded) rectal-(shielded) applicators; rigid/ flexible needles, templates	Fletcher Manchester, vaginal (shielded) rectal (shielded) applicators; rigid/flexible needles, templates
10. Accuracy of Source Position	± 1-mm with pneumatic check	± 1-mm	± 1-mm	± 1-mm
11. Source Arrangements and Dose Calculations	Point sources individually constructed to yield any desired distribution	Stepping source in 0.5-cm or 1.0-cm steps; 20-steps, 20-cm length covered	Stepping sources and dwell times to 999 sec in 0.1 sec increments	Stepping source and dwell times to 999 sec in 0.1 sec increments

Table 2 (b) (Cont'd.) - High Dose Rate Remote Afterloading Devices

Manufacturer or Vendor	Selectron (HDR) Nucletron Engineering BV (Netherlands)	Gamma Med II ISOTOPEN-TECHNIK Dr. Sauerwein GmbH & Co. (Germany)	Gamma Med IIi ISOTOPEN-TECHNIK Dr. Sauerwein GmbH & Co. (Germany)	Gamma Med 12i ISOTOPEN-TECHNIK Dr. Sauerwein GmbH & Co. (Germany)
1 Dose Rates	High	High	High	High
2 Modality	Intracavitary Intraluminal Intracavitary	Intracavitary Intraluminal	Intracavitary Interstitial Intraluminal	Intracavitary Interstitial Intraluminal
12 Uses Conventional RTP Software for Dosimetry?	Yes, or uses dedicated IBM-PC and software	Yes; Busch Isodose Atlas, IBM-PC	Yes; also has compatible IBM-PC	Yes; also has compatable IBM-PC
13 Dose Optimization Available?	Yes; 300 optimization points	Yes; 60 optimization points	Yes, 60 optimization points	Yes; 60 optimization points
14 Bladder and Rectal Dosimetry		Can terminate treatment at preset doses	Can terminate treatment at preset doses	Can terminate treatment at preset doses
15 Source Container Maximum Storage Activity	^{60}Co, 10-Ci	^{192}Ir; 20-Ci	^{192}Ir; 20-Ci	^{192}Ir; 20-Ci
16. Special Features	Pneumatic checks of source positions	----------	Storage of 23 treatments	Memorize storage of all planned and treated patients
17 Number of Applicator Channels	3	1	12	24
18 Maximum Number of Sources in Projector	20	1	1	1
19. Maximum Number of Channels Used Simultaneously	3	1	1	1
20 SOURCES				
a Radioisotope	^{60}Co	^{192}Ir	^{192}Ir	^{192}Ir
Physical Size	Capsule 2.5-mm OD	1.8-mm × 3.8-mm	1.1-mm × 8.5-mm, or × 6.5-mm	1.1-mm × 8.5-mm, or × 6.5-mm
	500-mCi	20-Ci	10-Ci	10-Ci

The original low dose rate Selectron was designed for up to forty-eight spherical ^{137}Cs sources with activities from 370.-MBq (0.01-Ci) to 1.48-GBq (0.04-Ci) and included three channels for moving the sources into various gynecologic applicators. The current Selectron transfers pellets pneumatically and a microprocessor controls source pellet arrangements. The current device is available with either three or six channels; the latter allows treatment of two patients simultaneously.

The MicroSelectron LDR, a low dose rate interstitial unit, features fifteen channels used with a secondary storage safe that can accommodate up to 45 different source configurations. The unit can use either conventional ^{192}Ir seeds in ribbons or ^{137}Cs seeds in a preselected configuration.[35] The secondary storage safe allows the user to purchase and use a large number of sources designed for use in specific sites,

The Omnitron Model 2000 features a high dose rate 370.-GBq (10.0-Ci) ^{192}Ir source only 0.59-mm in outside diameter; it can be used with 20-gauge needles of 0.89-mm outer diameter or in a smaller catheter of l.l-mm outer diameter. The source has a total extension distance of 150-cm and steps in 1.1-cm increments. The OmniCath, a special catheter, features a releasable stainless steel marker that can be sutured in place. Sealed access posts on the distal end of the catheter allow fractional HDR treatments for as long as three weeks. When the catheter is removed, the proximal stainless steel marker is released and remains at the implant site.

The MINIRAD features sixteen channels, is particularly applicable for LDR interstitial therapy of the breast and prostate, and is designed to be disconnected from the patient once the initial source transfer is complete. Each patient has a dedicated source container and the unit can track up to fourteen different containers.

The LDR Inter-Pal C-38 features thirty-eight channels and also is designed to be disconnected from the patient once source transfer is complete. This unit allows the operator to use an electronic remote control device for source transfer. By the nature of their design, the

MINIRAD and Inter-Pal C-38 do not retract sources when personnel eater the patient's room after the procedure begins.

The l&channel MicroSelectron PDR uses a 37.-GBq (1.0-Ci) ^{192}Ir source to yield instantaneous dose rates up to 300-cGy/h which, when pulsed, (i.e., delivered in a few minutes during each hour) are believed equivalent to continuous low dose rates of about 50-cGy/h.[36]

Eight high dose rate devices are included Table 2. The Ralston 20B unit", available in Japan, was omitted as as no units have been sold in the United States.

Afterloading Facts Buchler unit[38] is a general purpose unit for interstitial, intracavitary, intraluminal, and intraoperative therapy. It has a twelve-channel indexer and can be loaded with either a point source (l-mm × l-mm active volume) ^{192}Ir or with a linear source (0.5mm × 5-mm active volume) ^{192}Ir. Sixty steps are available with incremented steps of l- to l0-mm for a maximum length of 300-mm.

The Curietron intracavitary HDR unit uses static ^{137}Cs capsules in source trains of desired lengths; inactive spacers are loaded to form source trains of the desired active lengths. The projector can contain up to 185-GBq (5-Ci) of ^{137}Cs and uses four sources at once. Numerous conventional GYN applicators (Fletcher, Henschke, etc.) are available, as are plastic applicators of the DeLouche or Chassagne type.

The Curietron-192 HDR unit is designed for interstitial treatments and uses a shifting mechanism that can move a 370.-GBq (10.0-Ci) ^{192}Ir source over 64-cm using thirty-two steps. The unit has twenty treatment channels.

The MicroSelectron HDR[39] features 4.5-mm long by 1.10-mm diameter ^{192}Ir capsule with an eighteen-channel indexer; it is designed for use with either interstitial or gynecologic applicators. The unit moves a 370.-GBq (10.0-Ci) ^{192}Ir source over 12-cm using forty-eight positions separated by 2.5mm or over 24-cm using forty-eight steps of 5-mm.

The Selectron HDR is designed for intracavitary and intraluminal treatments and contains twenty “Co pellets with a total activity of 370.-GBq (10.0-Ci). The unit is available with three channels.[40]

The Gamma Med II[41], an intracavitary unit, features a 740.-GBq (20.0-Ci) ^{192}Ir source that is moved by a stepping motor over the 20-cm length of an applicator, steps of either 0.5-cm or l-cm are allowed. The desired dose distribution is achieved by allowing different dwell times at each location. Model IIi of this unit features an indexer with twelve channels into which a single 370.-GBq (10.0-Ci) ^{192}Ir source can be moved sequentially for interstitial implants; a new unit, Model 12i, contains twenty-four channels, and allows forty steps of 0.l-cm to l-cm increment over 40-cm length.

AU of the devices listed feature numerous fail-safe systems to ensure safe operation and use numerous popular applicators adapted for remote operation.

III. PATIENT POPULATIONS, EQUIPMENT SELECTION, AND FACILITY DESIGN

A. Patient Populations and Equipment Selection

Selection of a particular remote afterloading device will depend on the types and numbers of patients to be treated, total project costs and funds available, and the radiation oncologists’ current treatment philosophies and willingness to adopt new methods of patient care. Obviously, facilities with large patient numbers (100 patients per year or greater) may find remote afterloading more practical and the costs less burdensome than facilities with small patient numbers. Some of the types of brachytherapy and common anatomic sites treated with remote afterloading devices are intracavitary (uterus, vagina, rectum), intraluminal (esophagus, bronchus, trachea), interstitial (breast/chest wall, head and neck, vaginal sidewall, pancreas) and surface (skin lesions treated with molds). Because of design constraints, some remote afterloaders may be unable to treat all anatomic sites.

Generally, in planning capital budgets, planners must not overestimate the number of patients available for treatment because they fail to understand exactly which types of manual brachytherapy may be replaced by remote treatment. For example, significant numbers of gynecologic patients often are treated with combinations of interstitial vaginal implants in conjunction with a conventional intrauterine tube; such a combination treatment cannot be given on some low dose rate afterloading units designed for gynecologic therapy.

Moreover, the number of patients treated yearly may be highly variable and determined by referral patterns that often reflect changes in staff physicians. In high dose rate treatments of the lung, one of the more popular procedures with HDR units, some patients planned for intraluminal therapy cannot be treated because they cannot tolerate catheter placement. In summary, when planning to replace a manual brachytherapy procedure with a remote afterloading procedure, careful retrospective reviews of prior patient treatments for several years are advised so realistic estimates of the numbers and exact types of procedures are obtained.

B. Facility Design - Low Dose Rate Units

Facility design often is dictated by whether one is planning a new facility or renovating an existing facility to accommodate a remote afterloading device. Renovation of existing patient rooms is most common for LDR units. Low dose rate remote afterloading units usually can be located in rooms used for manual afterloading (Figure 1). Corner rooms adjacent to electrical closets or stairwells are ideal if the regulatory licensing agency allows use of occupancy factors less than one for these areas. The room should be close to the nurses work station to minimize long cable runs for remote alarm systems and to allow visual surveillance by the nurses of the entry doorway, if possible, to minimize interruptions in therapy.

While bedside shields commonly used for manual afterloading procedures can be used in conjunction with remote afterloading units (Figure 2), they offer several practical disadvantages. In smaller rooms, there is little space remaining around the bed if both the LDR

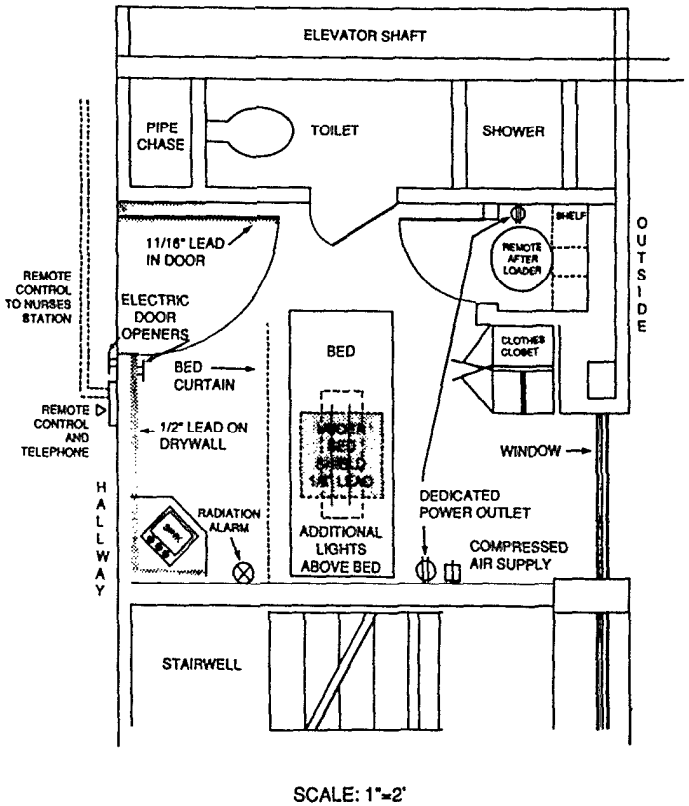


Figure 1. A small (11' by 9') second floor hospital room renovated at a cost of $59,000 to house an LDR remote afterloading device for gynecologic treatments. (Courtesy G. P. Glasgow, Maywood., IL). This room features an internal storage closet in which the LDR unit is stored when not in use. A projection shield (1/2" lead) beneath the bed shields the area below, 1/4" lead (not shown) covers and is suspended from the ceiling above. Note the compressed air supply, dedicated electric outlet, radiation monitor, remote control and telephone, power assisted door opener, 1/2" lead wall shields, and supplemental lights over head.

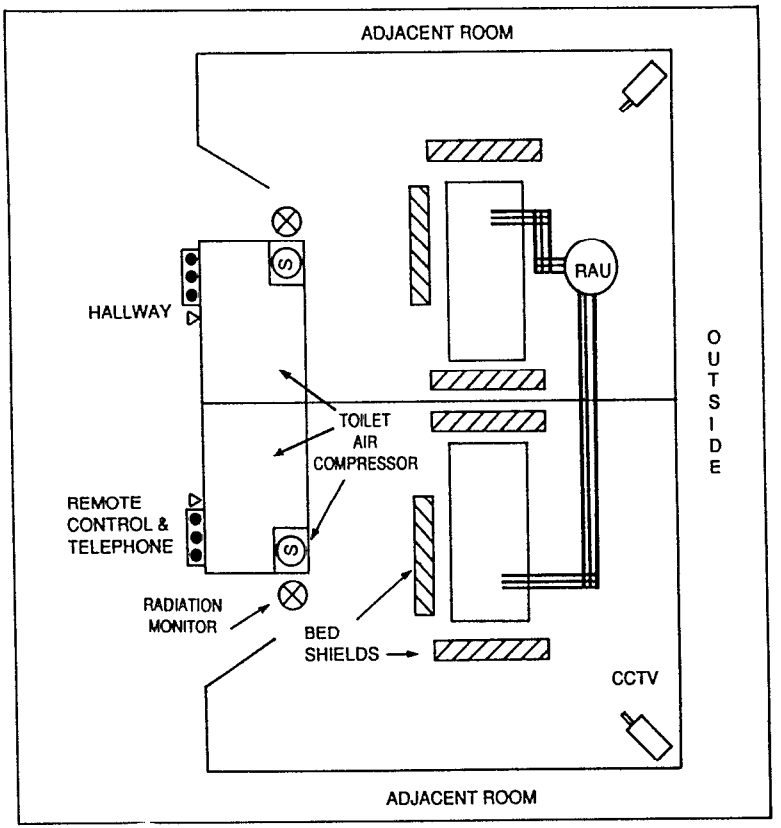


Figure 2. A two room treatment facility for gynecologic treatments, using single remote afterloading unit (RAU). The hallway and adjacent patient rooms are shielded using portable bed shields. (Courtesy of P. W. Grigsby, St. Louis, MO).

unit and bed shield are present; sometimes nurses move bed shields to facilitate patient care and fail to reset them in required shielding positions. The weight of bed, patient, bed shield and LDR unit are all concentrated in a small area and can approach the structural "live load" limit of the floor; the floor structural load limit must be carefully reviewed when adding heavy radiation shielding and equipment to any existing structure.

While shielded walls generally are more expensive than bedside shields, they offer the practical advantage of always being intact and allow more useable space in the room. A closet adjacent to the room or in the room (Figure 1) can be used for storage of the LDR unit when not in use; this allows the room to be used by patients not receiving brachytherapy. Ancillary support equipment, such as an air compressor used with pneumatic units, can be housed here to reduce noise in the treatment room. Ceiling and floor shielding may be required for adequate protection of patients or personnel; a projection shield placed in or beneath the bed is a practical alternate to shielding the floors for some rooms.

The best entry way to the room features a small maze (Figure 3) with the operator's control inside the protected maze. Usually this design will eliminate any shielding in the door and keep all operating controls secure inside the room. Unfortunately, many existing hospital rooms are too small to allow even a small maze. Depending on the bed location relative to the door, power assisted shielded doors (Figure 1) may be required as in radiation therapy vaults. Door interlocks that retract the sources when the door opens are usually required. Operating mechanisms placed outside the room in an adjacent hallway (Figure 1) are less secure from unauthorized use than those located inside the room in a mare, but location on a hallway wall adjacent to the door is common. Patient room lights are often inadequate. Supplemental lights over the bed will make it easier to see source guide tubes and check applicators protruding from the patient. An independent radiation monitor in the room generally is required. As it will be "on" when the patient is treated, some forethought should be

Dedicated Low Dose Rate Remote Afterloading Room

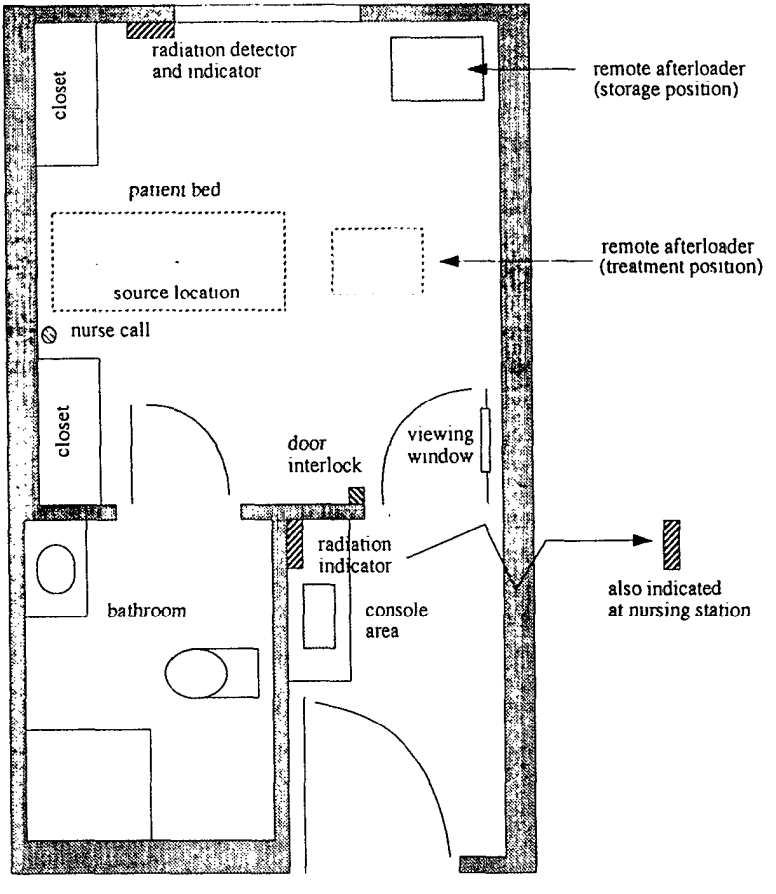


Figure 3. A dedicated LDR remote afterloading room with a small maze entryway and viewing window. (Modified from B. M. Wilson et al., Med Phys 13, 608, 1986, courtesy of J. D. Bourland, Rochester, MN).

given to its features and location. An audible alarm is undesirable; a continuously flashing light that indicates the source(s) is out of unit should be located such that it is viewed by those entering the room, but visually shielded so it does not disturb the patient.

Viewing of the patient is generally through a window in the maze wall (Figure 3) or by remote video camera with monitor located at the nurses station. Most LDR units feature a remote system status indicator with audible and visible indicators to allow nurses to monitor treatments. Often an audible, repeating "beep" that indicates therapy is underway is an unacceptable distraction to the nurses working at the work station.

Special attention is required for electrical power outlets; the LDR unit should be on a dedicated circuit as well as on the facility's emergency power circuit. A power conditioner may be required to stabilize incoming power. An adequate number of electrical outlets must be available in the room as patients can have numerous additional electrical monitors, each requiring its own power.

Generally, existing hospital rooms often are too small to accommodate ancillary equipment such as x-ray tubes and anesthesia equipment, which one may consider having in a new facility.

For a low or medium dose rate unit, it is imperative to know the maximum amount of radioactive materials and type to be used at one time, and their duration of use, (e.g., length of treatment sessions), and the projected workload of the unit. Licensing the facility will generally require compliance with the three traditional requirements of the USNRC and its Agreement States; namely, that the dose equivalents in adjacent unrestricted areas be (1) less than 0.02-mSv (2-mrem) in one hour; (2) less than 1-mSv (100-mrem) in 7 days, and (3) less than 5-mSv (500-mrem) in one year. The recent NCRP[42] and ICRP[43] recommendations of 1-mSv (100-mrem) annual effective dose equivalent for members of the general public continuously (frequently) exposed to radiation have been adopted by the USNRC,[44] with 5-mSv

(500-mrem) allowed by license authorization. Realistic estimates of the maximum amounts of radioactive materials to be used for specific durations are required in satisfying these conditions.

In a new facility it may be possible to include in the treatment suite other desirable ancillary equipment (Table 3), such as dedicated localization equipment required to assist with and confirm applicator placement, provisions for anesthesia, medical gases, special lighting, treatment tables and storage of these items when not in use.[45] Careful planning with departments that provide these services will be required because there are often emergency care reasons or other hospital policies that preclude anesthesia performed anywhere other than the primary operating rooms.

If anesthesia and diagnostic x-ray equipment are not located in the actual LDR treatment suite, forethought regarding where these procedures are to be performed is required.

Finally, a cable pass for dosimetry calibration equipment is useful to allow source calibrations and quality assurance dosimetry procedures to be performed from outside the treatment room.

C. Facility Design - High Dose Rate! Units

The features of an HDR therapy suite will depend on the anatomic sites to be treated, the annual number of patients, the radiation oncologists' philosophies and treatment regimens, the space available, and the availability of funds. Instantaneous dose rates around HDR units with 370.-GBq (10.0-Ci) sources preclude their use in conventional rooms unless patients are placed in specially designed local shielding areas or devices within the room.

The size of a dedicated HDR vault often is determined by the amount of ancillary x-ray imaging equipment installed. A small vault, 55-m (18') by 5.5-m (18'), will generally require 60-cm (2') thick concrete walls (specific density 2.2-g/cm^3) for a 370.-GBq (10.0-Ci) ^{192}Ir source (Figure 4). Bourland describes, for a Buchler HDR unit, a vault 8-m

Table 3. Equipment List: Dedicated Remote Afterloading and Minor Procedures Suite

- Anesthesia area: Medical gases and vacuum; designated location and electrical power for patient monitoring equipment; remote displays
- Audio communications
- Visual communications: 2 systems
- Sink/scrub area
- Patient procedures table
- Overhead track-mounted or C-arm x-ray unit with fluoroscopy
- X-ray generator location
- X-ray control console
- Remote afterloader control console
- In-room radiation detector
- In-room and remote radiation indicators
- Remote afterloader storage and treatment locations
- Operating room/procedures light
- Storage applicators and medical supplies
- Door interlock
- Treatment applicators
- Applicator positioning clamp: Integral with procedures table
- Emergency off buttons at console, in maze, and in room
- Emergency lighting: Wall or ceiling mounted
- Emergency power for selected equipment: Audio, video, anesthesia patient monitoring, lighting, radiation detectors and indicators; remote afterloader
- Optional dedicated scrub area
- Optional halon fire protection: Halon reservoir and discharge head(s)
- Optional treatment planning workstation

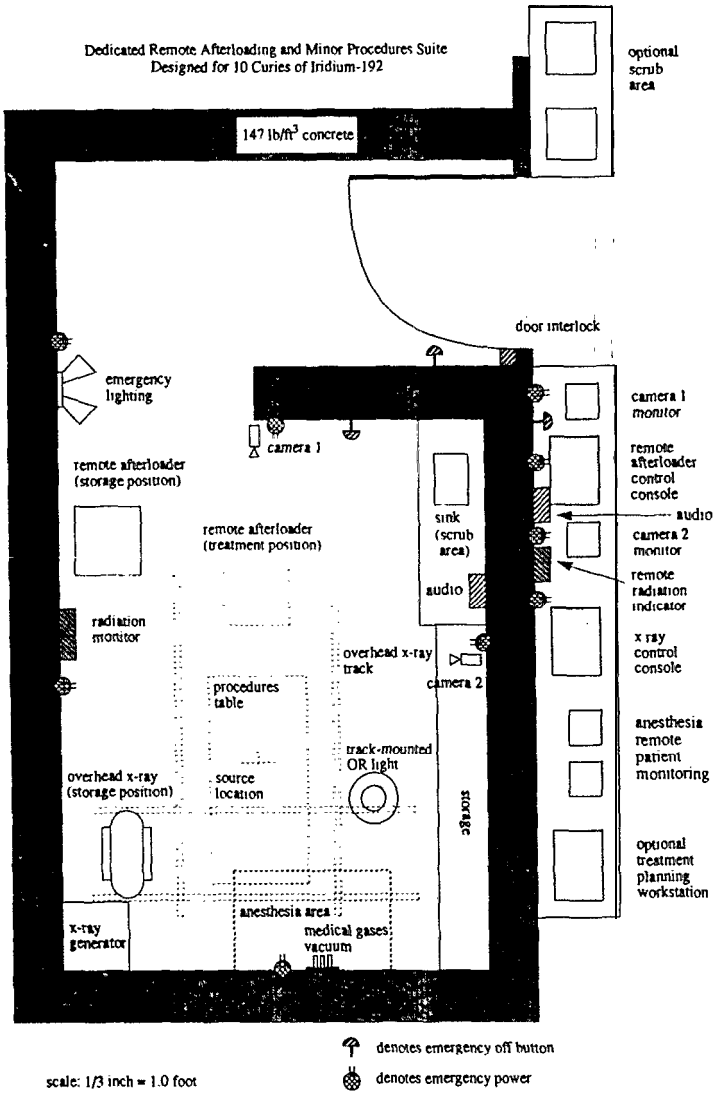


Figure 4. A dedicated HDR remote afterloading treatment suite with ancillary equipment. (Modified from Ref. 45; courtesy of J. D. Bourland, Rochester, MN).

(26.25') by 6.4-m (21') with 46-cm (18") concrete walls, well equipped as a minor procedure suite.[45]

Radiological safety requirements for a dedicated HDR vault are essentially those required for a cobalt teletherapy vault. These include positive action door interlocks that retract the source when the door is opened, and an emergency button, that, when pushed, will retract the source. Both of these will not allow the source(s) to leave the shielded device until the proper reset sequence is completed. Other features include warning lights, visible and audible alarms, remote closed circuit video camera (CCTV) and intercommunication devices for monitoring patients, radiation detector independent of the HDR, visible access alarms above the maze door, and a cable pass for dosimetry cables.

A vault equipped for minor procedures (Table 3) will require operating room features, such as medical gases, overhead operating room lights, anesthesia equipment and overhead radiographic and fluoroscopic x-ray tube, all in support of bronchoscopy, esophageal, cervical, and other applicator placement procedures.[46] Generally construction costs “per patient” will be high unless a large number of patients are treated annually.

If an existing teletherapy or linac vault is used, the radiological safety features listed are still required, While most vaults possess adequate shielding for 370.-GBq (10.0-Ci) Ir-192 sources, a vault survey with a source of the activity and type proposed will confirm the adequacy of the vault and identify “hot spots” or shielding defects.[47] Special care is required to ensure that the teletherapy unit or linac cannot be turned on while a HDR procedure is underway; usually this can be achieved by using interlocks. One simple procedure keeps operating keys for both units on a single key ring with no duplicate keys available at the units. It is usually difficult to add minor procedure equipment to an existing vault. Usually an adjacent simulator room can be used for applicator placements and localization procedures, and can be modified as a minor procedure suite. The major disadvantage using an existing teletherapy vault is scheduling patients for remote afterloading procedures in a vault used for external beam patients.

D. Costs

Annualized costs of a remote afterloading facility are given by:

$$\frac{(1 + r^n) \times r}{(1 + r)^n - 1} \times \text{Capital Costs} \qquad [1]$$

where *r* is the annual discount or depreciation rate, and *n* is the number of years. Capital costs generally consist of the equipment cost, long lived radioactive sources, room modification expenses, ancillary equipment, but would exclude annual costs of service contracts, personnel salaries, and short lived radioactive sources. For example, for a low dose rate unit that costs $128,000 with room modification costs of $59,000, the annualized cost for ten years at 10% is about $30,000. Low dose rate remote afterloading generally is more expensive than manual afterloading; Grigsby[48] estimated that procedure costs for LDR brachytherapy were at least 25% greater than the costs of similar manual brachytherapy procedures.

IV. LICENSES AND LICENSE COMPLIANCE

A. Licensing Agencies

Purchasers of remote afterloading units must apply for a license or license amendment with the appropriate regulatory agency, either an Agreement State agency ***or*** the United States Nuclear Regulatory Commission for non-Agreement States and for federal hospitals. The purchaser should always ask the vendor to prove, by supplying a copy of the registration, that the device and sources are on the Registry of Radioactive Sealed Sources and Devices. Equipment not on this Registry cannot be licensed; license applications can be delayed for many months while the vendors attempt to place new designs of devices on this Registry.

B. License Content

With respect to the license application content, include only the absolute minimum information required. The license, and any attached documents, is a legal standard against which compliance actions will be judged. Quality assurance procedures that you intend to do **faithfully** at regular intervals should be excluded unless required by the regulatory agency. A typical license application must:

1. Describe the source(s) (radionuclide, size, manufacturer, activity, and physical construction).

2. Describe the manufacturer and model of the remote afterloader.

3. Describe the intended use (cancer therapy in humans).

4. Describe the intended users, and their training and experience.

5. Describe the radiation detection instruments to be used.

6. Describe (to scale) the floor plan of the facility, identifying the doors, windows, wall materials and distances to closest occupiable points around, above, and below the facility.

7. Prove, by calculations, that selected adjacent areas comply with the required regulatory standards, likely to be 0.02-mSv (2-mrem) in one hour, 1-mSv (100-mrem) in seven days, and 5-mSv (500-mrem) in one year for non-restricted areas, and 1-mSv (100-mrem) in one year for members of general public continuously exposed. The 5-mSv (500-mrem) per year may be allowed by license authorization by the USNRC.[44]

8. Describe area security, including access to operating keys, door interlocks, radiation warning systems, and for HDR units in linac

vaults, ensure that any other device that produces radiation cannot be turned on simultaneously with the HDR unit.

9. Describe patient viewing and communication systems.

10. Describe the detection instruments, calibration procedures, calibration frequency, leak test procedures and frequency, and the qualifications of those performing these tests.

11. Describe the quality assurance program, including either pre-treatment or daily quality assurance procedures and procedures to be performed at other selected (monthly, quarterly, annually) intervals.

12. Describe the training of individuals performing the source changes (normally vendor representatives).

13. Describe the training and frequency of retraining of individual operators. (Annual training may be excessive; retraining at two years is more reasonable.)

14. Describe the personnel radiological monitoring program. (Quarterly badge changes may be adequate.)

15. Describe the emergency procedures, where they are posted, and the frequency of emergency “dry runs”.

16. Describe provisions of disposing of decayed sources (usually by return to vendor).

17, Describe the titles and locations of manuals available to personnel.

C. License Compliance

You must do what you promise in your license, so caution is advisable; you can always do more, but never less! For example, calibration and

quality assurance procedures which may change over time should be excluded from the license, if possible, to allow the user some flexibiity in developing a strong, useful quality assurance program. The regulatory agency may be particularly interested in independent verification of planned treatments and other "pretreatment" quality assurance procedures due to recent misadministrations with remote afterloading units.[18,19] License compliance requires timely compliance with and thorough documentation of each item in the license that requires a written record. Particular forethought must be given as to how these written records will be maintained to prove compliance during regulatory inspections.

V. RADIATION CONTROL (SAFETY)

To write the license application requires that radiation control procedures be developed prior to the **license** application. Regardless of the type of remote afterloading unit, radiation control procedures generally can be grouped into (1) safety features inherent in the remote afterloading unit; (2) initial radiation survey of the facility and subsequent patient surveys; (3) routine precautions required during normal use; (4) precautions required during source exchanges;(5) emergency procedures; (6) training and retraining of personnel.

A. Design Safety Features

AU remote afterloading units should have certain safety features, some of which are listed in Tables 1 and 2. These include, but are not limited to:

1. A back-up battery system that will prevent loss of computer data during power failure; ideally it will also allow a power-interrupted treatment to continue.

2. An interrupt button to allow treatment to resume after a planned interruption.

3. A simulation mode using dummy sources to test source guide tubes and applicator clearances immediately prior to treatment.

4. Clear console indicators that show when the source is “in” and “out” of the safe and when the door is “closed” and “opened”.

5. A “last resort” mechanical system for manually returning the source to the safe in the event other electrical source return mechanisms fail.

B. Radiation Surveys

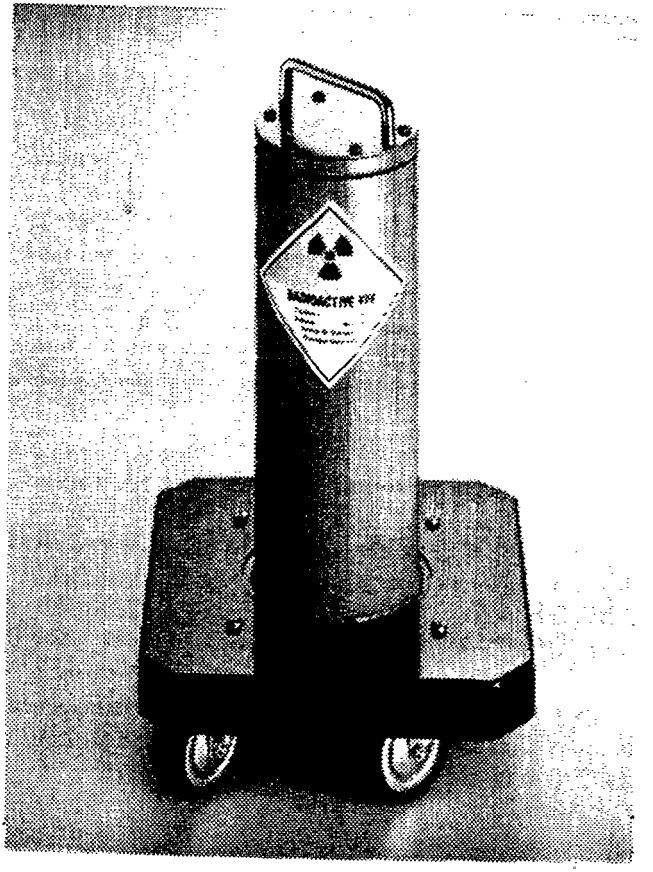
After installation of the remote afterloading unit and sources in the treatment facility, a radiation survey must be performed under the conditions assumed in the license application, to confirm that the instantaneous exposure rates around the unit do not produce dose equivalents in excess of those projected in the license application.

For the routine use of LDR and MDR units, it may not be necessary to measure the exposure rate outside the patient’s room and in adjacent rooms for each patient if the license application established alternate procedures to prove that exposure rates in unrestricted areas comply with regulatory standards; this is preferable to doing surveys for each patient.

C. Routine Precautions

Routine radiation control procedures include, but are not limited to, having available in the treatment facility:

1. An emergency container (Fire 5) and long handled tongs for retrieving the source(s) if it (they) break(s) from the drive mechanism or fail to return to the primary safe. This emergency container should be large enough and deep enough to accept the entire applicator assembly that is in a patient, if it is ever necessary to remove an entire applicator with sources intact in it. During treatment, the



Fire 5. A mobile emergency shielded container. Long handled forceps to assist with source retrieval should be available with the container. (Courtesy of Mick Radio-Nuclear, Inc., NY).

container must be positioned sufficiently close to the patient so that it can accept the applicator with source intact in it, if necessary. Medical supplies and devices to assist with emergency applicator removal should be available.

2. A radiation survey meter.

3. A sign **"DANGER - DO NOT ENTER - OPEN SOURCE",** for immediate posting, if required.

Documented exit radiation surveys of patients, which may seem redundant, are still good practice, and may be required by license to confirm there are no sources in the patient, depending on the regulatory agency and license application content. An independent visible radiation detector in the room generally is required and may serve as the exit survey device. However, it must have sufficient sensitivity to respond to the smallest individual radioactive source used in the device at the maximum distance the source could be from the detector. A hand-held Geiger-Mueller survey meter is best for exit surveys.

Finger radiation monitors for personnel operating units are a good practice. While unusual events, such as a source jammed in the applicator, are infrequent, if personnel are involved in an emergency, their finger rings, in conjunction with their whole body personnel monitors, will help provide estimates of dose equivalents received during emergencies.

Posted emergency procedures should address the appropriate sequence of actions if the source(s) fails to retract and explain the next sequence of actions if the first corrective action sequence fails to retract the source(s), e.g., describe what actions to take if the source(s) fails to retract when the “emergency off’ is pushed, describe what sequence of actions to follow if the mechanical retraction system fails; describe who to call next if no one responds at the first emergency number called, etc.

Finally, well described procedures should exist for source(s) retrieval if the source totally detaches from its drive mechanism and falls to the floor, or remains in an applicator in the patient. Particular care must be given to emergency procedures for HDR sources because the exposure rates are so high. Exposure rates l-m from an unshielded 370.-GBq (10.0-Ci) ^{192}Ir source are about 4.6-R/h.

D. Manuals

An Operator Manual should be at the control console or nearby area and at a minimum:

1. Describes the functioning of the control console options.

2. Describes how to program a treatment and supplies a sample program.

3. Describes how to check that the program and time adjustment factor (if applicable) are correct.

4. Describes emergency procedures (these shall also be posted).

5. Provides a list of names and telephone numbers of people to contact in case of an emergency (these shall also be posted).

6. Provides a check list of quality assurance procedures to be performed and the name and number of the person to call if quality assurance is not acceptable.

7. Provides a list of error messages, if applicable.

A Physicist/Engineer Manual should be easily accessible that, at a minimum:

1. Describes radiation survey procedures when receiving new sources.

2. Describes procedures for returning old sources.

3. Describes source change procedures.

4. Provides a floor plan for room surveys to be performed.

5. Provides a plan and check list of other radiation surveys to be performed.

6. Provides a check list and forms for quality assurance procedures to be performed.

7. Provides names and telephone numbers of people to calf in case of an emergency.

8. Describes source calibration procedures and provides forms for calibration.

If nurses have a responsibility for operating a remote afterloading unit, a Nurse's Manual should be at the control console which, at a minimum:

1. Describes the functioning of the control console options.

2 Provides instructions on how to retract sources and verify that they are retracted prior to entering the room.

3. Describes emergency procedures including instruction on how to handle a dislodged source.

4. Provides a list of names and telephone numbers of people to contact in case of an emergency.

5. Describes the physical features of the sources used.

6. Describes the functioning of the independent radiation monitoring system.

7. Specifies the radiation warning signs to be posted.

E. Source Exchange Procedures

The frequency of source(s) change is at the discretion of the institution. Although detailed instructions to accomplish these changes should be part of the Physicist/Engineer Manual, source changes must be done only by qualified and properly trained personnel as defined in the license application.

Upon receipt of new sources, appropriate radiation safety procedures must be followed. Ideally, the transfer of sources from the safe to the shipment container and vice versa should be done remotely from the control console outside the room, or from a properly shielded area in the room.

Policies and procedures for handling radioactive sources of remote afterloaders are in general conceptually the same as for conventional brachytherapy sources, but obviously vary depending on the amount of radioactivity in the sources and the frequency with which sources are exchanged. They generally include, but are not limited to:

1. Procedures for receiving and returning sources (allow adequate time after source exchange to prepare and ship the decayed source; six weeks is a good time period).

2. Frequency of leak testing (usually every six months). If sources are retained for a shorter period of time, it is sufficient for the user to rely on the manufacturer's leak test, provided it is recent enough.

3. Frequency of inventory checks (usually quarterly); as remote sources are self contained it is possible to write alternate procedures in the license that substitute for a physical inventory.

4. Specifications of radiation surveys to be made with each source change in order to:

a. Ensure that all sources are either in the safe of the remote afterloader or in the shipment container.

b. Determine the exposure rate at agreed points around the safe. These rates must be within the limits set by the regulatory licensing agency.

c. Determine for "exposed sources" that the exposure rate at points outside the treatment room, identified in the license application, are within the limits set by that agency.

5. If patients receiving multiple fractions are in therapy when a source change occurs, it is particularly important to confirm that the newly established source activity is used for calculation of their treatment times.

6. Frequency of dose rate measurements in and around areas where sources in remote afterloading units or supplemental safes are stored when not in use.

F. Emergency Procedures

Some emergency procedures have previously been discussed under "routine procedures", e.g., that plans should be made for emergencies. In preparing emergency procedures it is important to have separate procedures established for electrical (power loss) emergencies, fire (ii the treatment facility or in the remote afterloading device) emergencies and radiation emergencies. For the latter, typical "emergencies" include (1) source(s) failing to seat in the applicator, aborting the treatment; (2) potential interruption of the therapy because the sources dislodge from the applicator, the applicator dislodges from the patient, or a source guide tube becomes loose or ruptures; (3) clock or timer failure during therapy, (4) at the end of therapy, the source(s) fail to retract, and (5) the sources or source capsule break away and spill the radioactive material in the room. A major emergency would be losing a source in the patient, e.g., some accident in which the applicator fails and the source breaks loose and lodges in the patient. Some consideration must be given to the actions required if this were to occur. While open-ended catheter procedures have been used with remote

afterloading units, they are not recommended because of the small possibility of losing a source within a patient. Procedures exist for placing opened ended catheters using a guide wire; after catheter placement, but before the catheter is used with the radioactive source, the open end is closed by inserting a small metal sphere into the tapered end of the catheter.

We emphasize that separate written procedures must be established for each category of emergency. These procedures must stress alternate actions to take if the first emergency response fails. The procedures must not only be posted, but practiced by those responsible for operating the units and treating the patients.

G. Training Courses

As part of the purchase price, the vendor should include a training course to be attended by those who use and operate the equipment, usually physicists, engineers (if applicable), dosimetrists, technologists, and/or chief technologist and health physicists and attending physicians if they are operators.

The course should thoroughly review:

1. Available applicators and their proper use.

2. The functioning and operation of the unit under normal conditions.

3. The function and operation of the unit under emergency conditions.

4. All safety features.

5. Radiation protection procedures.

6. Suggested quality assurance procedures.

7. AU aspects of the dose calculation (treatment planning) system, if applicable.

The physicist and engineer should also receive detailed instruction on source exchange procedures. They cannot be considered qualified to exchange sources until they have met whatever requirements the regulatory agency has established for those allowed to exchange sources. Generally, this issue must be addressed in the license application. Proper documentation of the contents of this training and attendance records of those who attend arc generally required by regulatory agencies.

Generally, the license will have been written to identify the individual physicist, safety officer, or others who are then responsible for instructing the nursing staff or other staff members who become involved in operating the unit. The identified individual, usually the radiologic physicist or health physicist, is responsible for providing instruction on radiation safety procedures to all personnel caring for patients treated with the remote afterloader, including retraining at the intervals specified in the license.

VI. ACCEPTANCE TESTING

The acceptance tests establish the baseline operating performance parameters of the remote afterloading device and facility. They can be broadly divided into (1) the mechanical and electrical operation of the remote afterloading device and radiation monitors, (2) the mechanical and electrical features of the facility, (3) the integrity of the applicators, (4) the integrity and proper operation of the radioactive source(s), and (5) the proper operation of the computer that generates isodose distributions. Numerous authors have reported acceptance tests and quality assurance procedures for remote afterloaders.[49-57] The calibration of the radioactive source(s) and dosimetry are addressed in a later section.

A. Remote Afterloader Tests

Acceptance testing of the mechanical and electrical functions of the remote afterloaders includes, but is not limited to, confirming:

1. That all console functions (key switches, main power, battery power, source ON/OFF, door OPEN/CLOSE, etc.) and indicators perform properly.

2. That the source(s) retracts at the end of preset times, retracts when interrupted, retracts under loss of electrical power or air pressure if so driven, retracts if source guide tubes or applicators are connected in an improper sequence, improperly connected, constricted or blocked, and retracts when the emergency button(s) is used. Confirm appropriate console displays or printed tape error messages by producing or simulating a planned “failure” or “error”. Confirm that programmed data (duration of remaining treatment time, etc.) is retained if source retraction or other unplanned interruptions occur.

3. The battery voltage under load is adequate and that operating functions retained under battery power indeed work.

4. The accuracy of timers relative to an independent clock, for periods similar to those proposed for treatments; determine end-time effects. End-effects may not be a medically important parameter for LDR units or HDR units, but may be a consideration during certain source calibration procedures, particularly those involving chamber calibration at multiple distances.

5. The accuracy of any decayed source(s) activity calculated by computer. Decayed source activity tables should be available to confirm source activities calculated by the remote afterloading unit.

6. That any multi-channel indexer functions properly and moves the source(s) in proper sequence into the correct channels.

7. That appropriate backup systems function properly during simulated power failures and/or air pressure losses.

8. That the mechanical source retraction system works; it may not be possible to simulate an "exposed source" condition on some units.

9. That any radiation detectors in the remote afterloader operate properly.

10. That program storage and recall function properly. Check that dwell times in stored programs are changed to reflect source activity at the time of use (unless the machine design requires entry of dwell-time patterns based on a given activity, e.g. 370.-GBq (10.0-Ci), with automatic adjustment of the real treatment time to allow for decay).

11. That leakage radiation rates around the device are acceptable.

B. Facility Testing

Facility testing includes, but is not limited to, confirming:

1. That any door interlock system retracts the source(s) when the door is opened and that the unit does not restart automatically when the door is closed.

2. That the source(s) cannot be driven out of the safe with the door open.

3. That radiation warning lights in the room and over the door function properly during planned and unplanned room entry. If other radiation producing equipment is in the room, particular attention must be given to the location and proper functioning of entry way radiation status lights so that it is clear *which* unit is producing radiation.

4. That the closed circuit television and intercommunication systems function properly.

5. That the independent radiation monitor in the room performs properly, using a radioactive check source, and functions during treatments.

6. That any other radiation producing equipment in the same room cannot be turned on simultaneously with the remote afterloading device.

7. That the radiation exposure rates and conditions **around the** facility comply with those included in the license application.

8. That emergency buttons in the room function properly.

9. That installed compressed air lines maintain adequate pressure under load and for the planned duration of treatments.

10. That any security system, required for the storage of the remote afterloader when not in use, functions properly.

C. Source Transport Systems and Applicator Tests

The testing includes, but is not limited to, confirming:

1. The integrity of the source guide tubes that transport the source(s) to the applicator(s). For sources transported by cables, source guide tube length is a critical parameter and source guide tube length gauges are used to confirm the length to l-mm accuracy. For pneumatic transfer of sources, air tubes must be inspected for hairpin leaks, constrictions, and other obstacles to source transport. Particular care should be given to testing the remote afterloader with all combinations of source transport tubes and applicators to ensure that faulty connectors do not exist.

2. The mechanical integrity of the applicators via visual inspection and/or radiographs. Confirm the presence and correct placement of any internal shields or other critical internal components within the applicator.

3. That any simulated (dummy) source designed to represent source position or placement and the radioactive source(s) both position properly, generally to l-mm accuracy, in applicators or at static locations in test devices. Radiographs of dummy sources in test devices or applicators (Figures 6, 7) with their mechanical positions indicated by pen-pricks or other external markers, if possible, combined with autoradiographs of the radioactive source(s) in the same device or applicators, will show any lack of coincidence between the position of the dummy sources and the position of the radioactive source(s). Ezzell[55] describes a device with eighteen channels (Figure 8) used for autoradiography; Jones[53] uses a strip of radiation sensitive paper for autoradiographs.

For simulated sources and radioactive sources, one can observe, by CCTV and transparent source placement check devices (Figure 9), that the sources will transport as planned, to l-mm accuracy, to preselected locations.

4. That the radioactive source(s) move accurately through the applicator(s) creating the desired radiation dose patterns. Visual verification (Figure 9) via CCTV and/or radiographs of simulated sources at numerous planned locations in test devices or in the applicators followed by autoradiography on the same film are required.

5. The radiation attenuation of applicators and deciding if attenuation corrections will be made in treatment planning.

D. Source Tests

Acceptance testing of the radioactive source(s) will include:

1. A careful review of the source(s) certificate regarding physical and chemical form, source encapsulation, and model number, to confirm that the source(s) delivered complies with those allowed

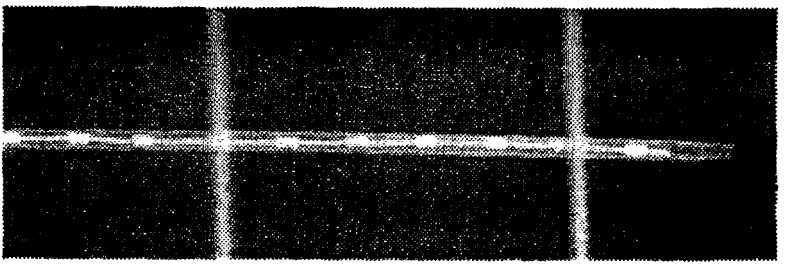
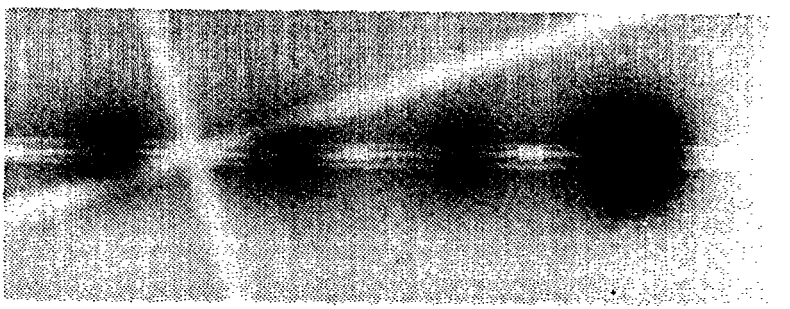


Figure 6. (a) Radiograph of simulated (dummy) source in a catheter;



(b) Autoradiograph of HDR source superimposed on the radiograph. Note the non-coincidence of the dummy and live source positions caused by failing to push the dummy source fully to the end of the catheter (N.B. Simulator field delineator wires should be removed from the field so they do not obstruct the images; that was not done here); (Courtesy of G. P. Glasgow, Maywood, IL).

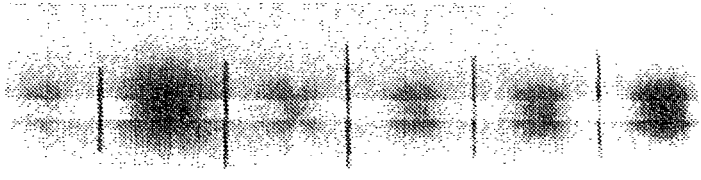
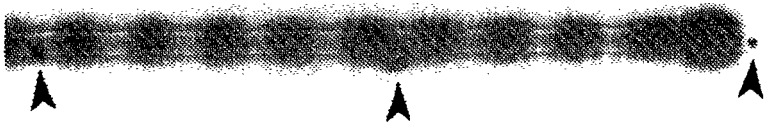


Figure 6. (c) Vertical lines mark the center of every alternate dummy seed, allowing measurements of the distances between the dummy seed centers and the centers of the radiation patterns produced by the live source;



(d) Pen-pricks in the film at known locations (5-cm intervals from the catheter tip) allow measurements of the live source radiation patterns relative to the end of the catheter (Courtesy of G. P. Glasgow, Maywood, IL).

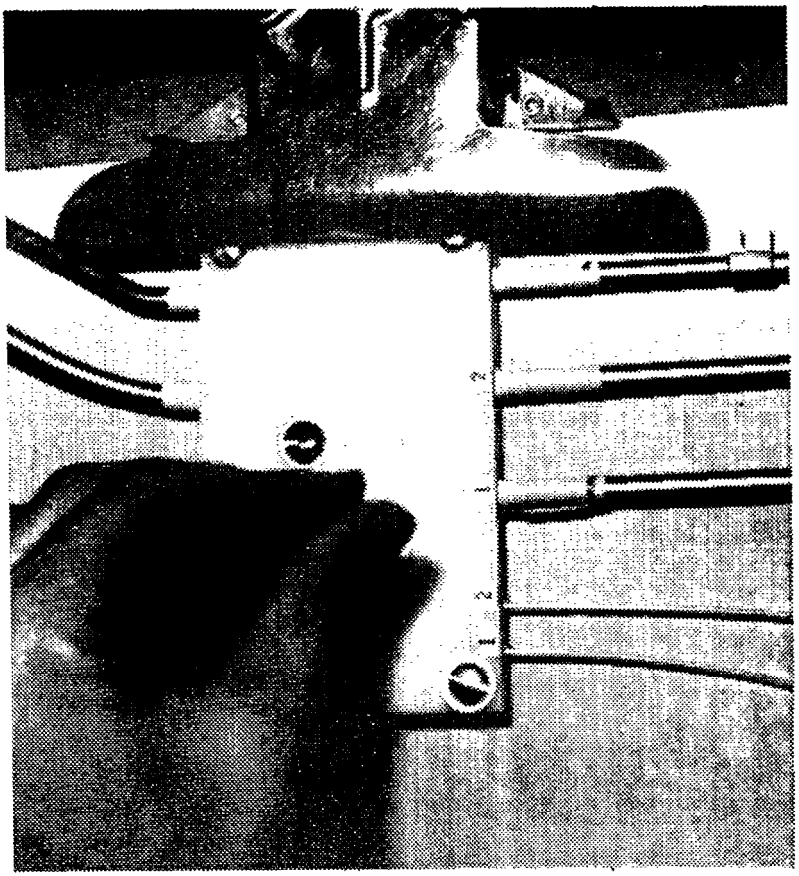


Figure 7. Device used for autoradiography to test source positioning accuracy. (a) Plastic jig with drilled pin holes to indicate the physical position of sources on autoradiographs. (Courtesy of G. A. Ezzell, Detroit, MI).

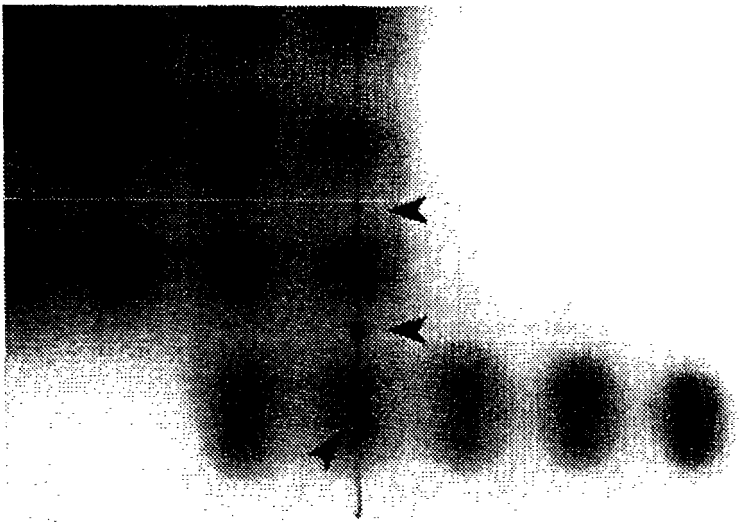


Figure 7. (b) Three pin holes made in the film, and joined by a line, pass through the source's center on the autoradiograph. (Courtesy of G. A. Ezzell, Detroit, MI).

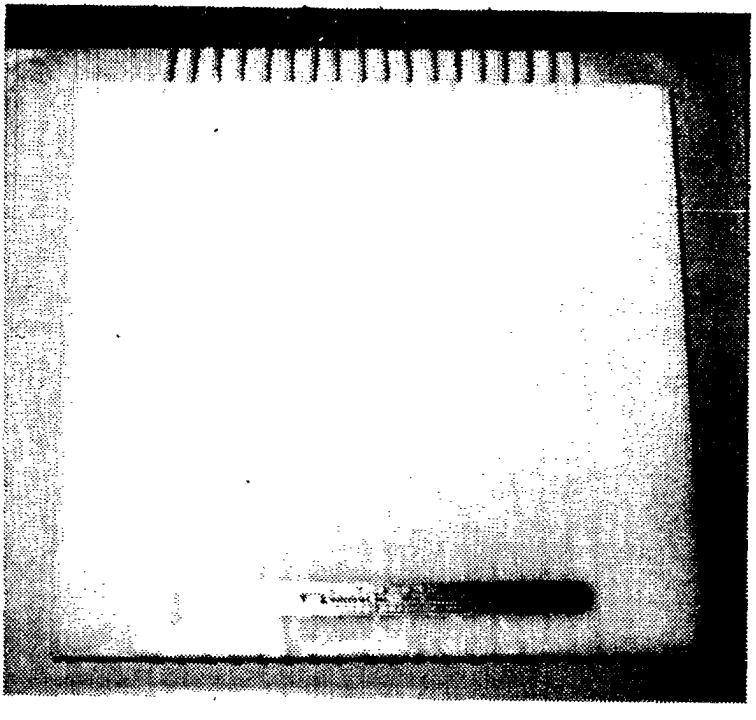


Figure 8(a). An eighteen channel autoradiography test device. (Courtesy of G. A. Ezzell, Detroit, MI).

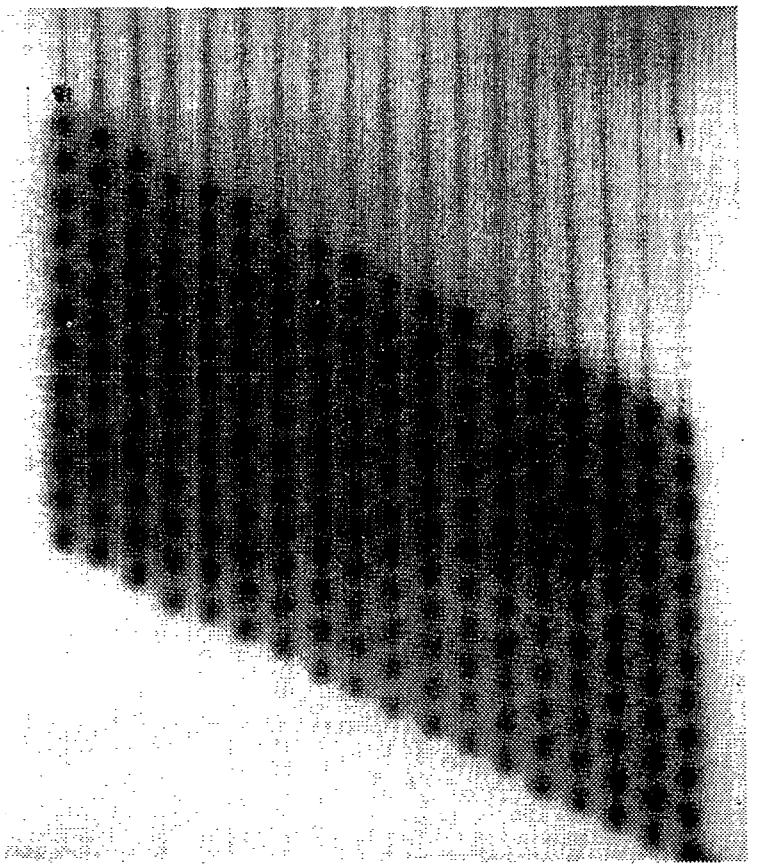


Figure 8(b). Autoradiograph obtained using the device (Courtesy of G. A. Ezzell, Detroit, MI).

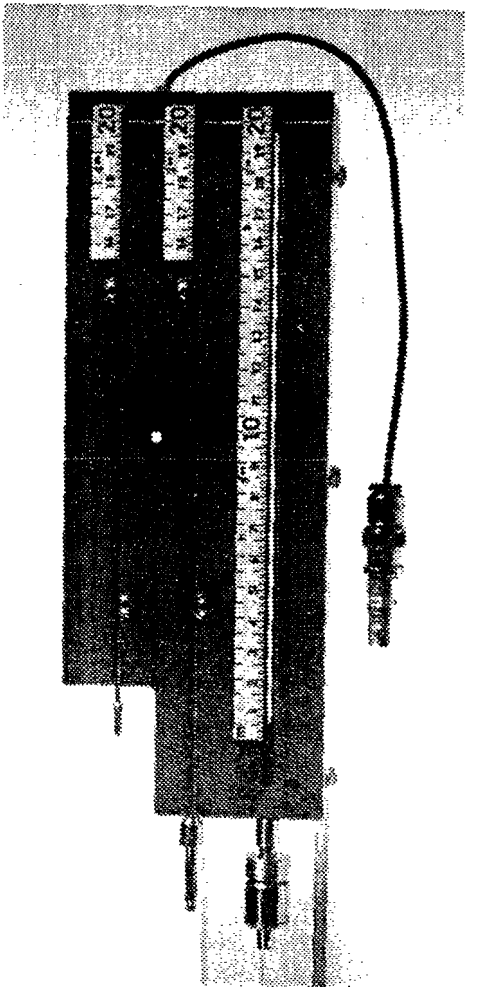


Figure 9(a). A visual alignment source position test device (Mick Radio-Nuclear, Inc., New York) modified by adding a diode to check source activity (Courtesy of J. Meli, New Haven, CT).

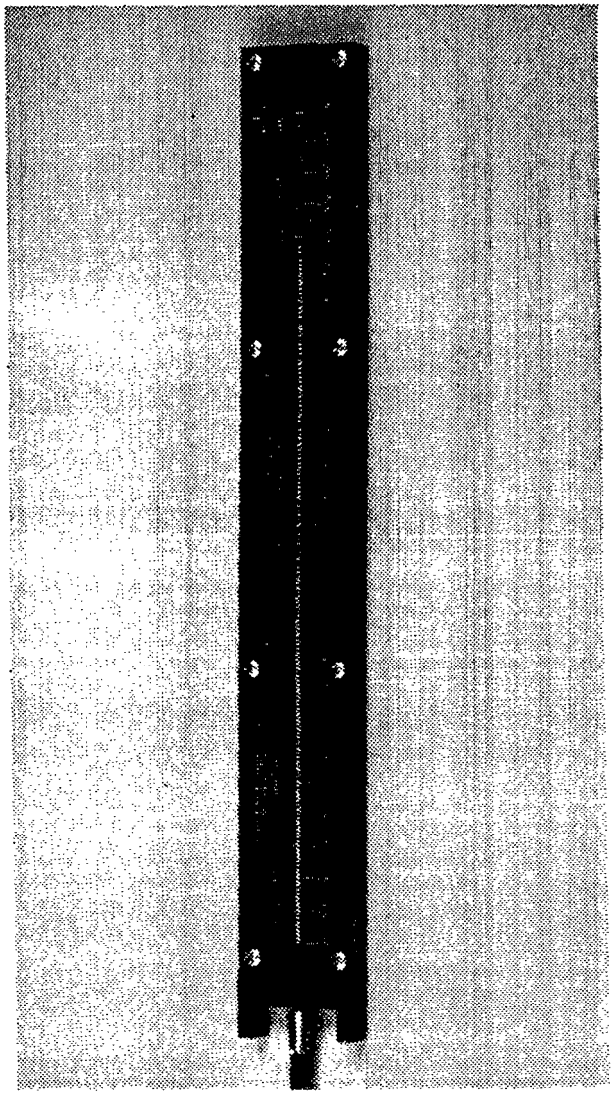


Figure 9(b). A visual alignment source position test device (Courtesy of Miles Mount, Nucletron Corp., Columbia, MD).

under the license. A source design drawing should be available as details of source(s) construction may be required for computer models of the source(s) and the resulting radiation dose distribution.

2. Determination of correct number of and the relative activities for multiple sources of the same design. A well ionization chamber may be used to determine relative activities as long as each individual source in the batch is measured in an identical manner, e.g., at the same position in the center of the well ionization chamber. Multiple autoradiographs of each source on one film and a comparison of relative optical densities is an alternate method, but requires greater attention to procedural detail.

3. Leak testing of the source(s). Swabs or filter papers moistened with water or alcohol are used to wipe either the source surface or the interior of the selected source carrier." Activity can be measured with calibrated GM tubes or scintillation counters that can detect 37-Bq (1.0-nCi). Often indirect leak testing is required by testing the interior of applicators or source guide tubes directly in contact with the source rather than direct leak testing of the source(s). Generally, the extent of leakage from a sealed non-gaseous source is estimated by multiplying the measured activity obtained by a factor of 10.[57] Normally, sources that have less than 185.-Bq (5.0-nCi) removable activity on their exterior surface are considered uncontaminated.

4. Determination of dose distribution anisotropy. Source construction and encapsulation generally produce dose distributions that are anisotropic, particularly near the ends of small linear sources (Figure 10). Often, these effects are neglected and the sources are considered point sources for dose computations. Generally, the user should determine if the dose anisotropy for a specific model source has been measured. Measuring dose distribution anisotropy is difficult, and few reports exist. Cerra and Rodgers" measured dose anisotropy for a Gamma Med IIi high activity ^{192}Ir source; dose anisotropy in low activity ^{192}Ir seeds was reported by Ling et al.,[59] and C. Thomason et al.,[60] as well as for ^{137}Cs seed sources. Siwck et al.,[61] reported on the dose anisotropies produced by adjacent spherical ^{137}Cs sources in a Selectron.

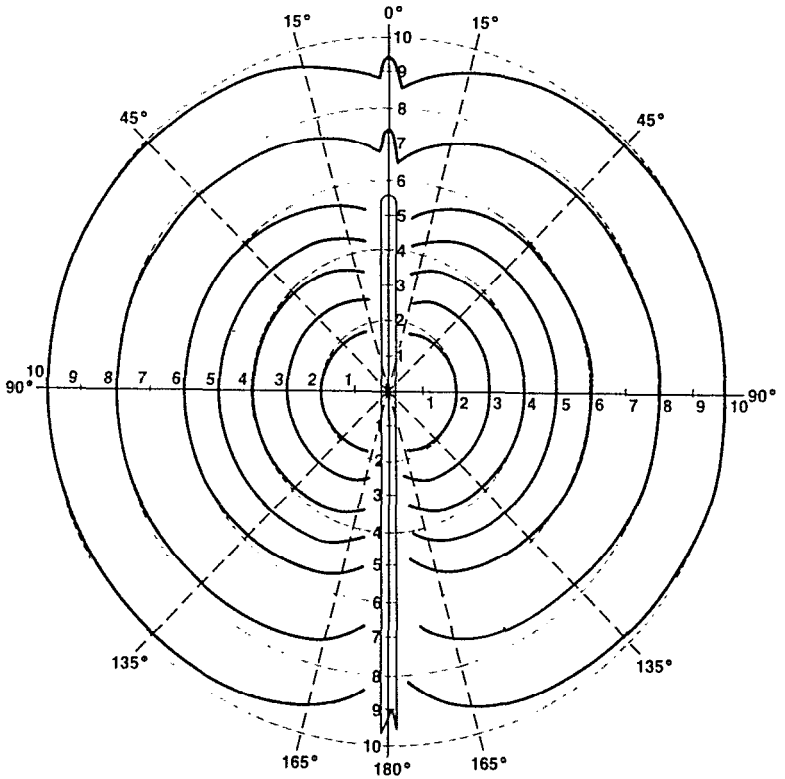


Figure 10. Measured isodose rate contours in water for a 370.-GBq (10.0-Ci) 0.5-mm by 5.5-mm ^{192}Ir Gamma Med II$_1$ source in an endobronchial applicator. The respective intensities (starting from the center) arc 1146-, 509-, 285-, 125-, 68-, and 42-cGy/hr/Ci. Axes arc labeled in centimeters. (Courtesy of F. Cerra and J. F. Rodgers, Washington, D.C.)

Users should determine, by measurement, if possible, or by review of the literature, the dose anisotropy of specific source models. Data for dose distribution anisotropy should only be used for the specific model sources reported and not applied to other sources.

5. Absolute calibration of the source(s). For remote afterloaders using single ^{192}Ir sources replaced several times yearly, it is most important to develop a consistent, reproducible method of calibration. For long lived sources, e.g., ^{137}Cs pellets, where the unit contains multiple sources of the same nominal activity, one needs to determine the average activity and standard deviation of the lot and confirm that they meet manufacturer-stated certificate values. Methods of absolute calibration are discussed in Section VIII of the report.

E. Brachytherapy Planning Computer

For any computer system that produces isodose curves for remote afterloaders, it is imperative that the user understand the algorithm and exactly how the doses are computed. The user may have to enter key parameters specific to a radionuclide and source model, or select parameters from an existing menu. Source activities may be expressed in megabecquerels, millicuries, apparent millicuries, milligram radium equivalents; alternately, the certificate may state the reference air kerma rate at l-m or air kerma strength produced by the source. AAPM Report 21, *Specification of Brachytherapy Source Strength,* [62] is a valuable guide to understanding these parameters.

Modifying effects of the source capsule on the dose distribution may be considered or neglected, depending on the ability of the computational algorithm to represent those effects; the same is true of the modification caused by source carriers or applicators. Tissue attenuation and multiple scattering corrections must also be considered. It is beyond the scope of this document to discuss all of these topics for the many radioisotopes, source models, and applicator systems available for use with LDR and HDR units. However, AAPM Radiation Therapy Committee Task Group 40 has recommended that,

for a single source, the computed isodose curves have a tolerance to within 2% along the radial dimension of linear sources and a 5% tolerance for isodose curves near the end of the sources. Jayaraman and Lanzl[63] noted, however, that corrections for source capsule effects, in linear low dose rate sources, have uncertainties of about ± 2%. Moreover, tissue attenuation and multiple scattering corrections at l-cm radially from a line source vary from 2% to 4%, depending on the isotope. These authors conclude that the overall uncertainty in the dosimetry at regions of clinical interest will be limited to about ± 6%, depending on the radioisotope and source model.

Consistency is more important than absolute accuracy. Each user must establish an initial baseline source dosimetry; single source isodose distributions in air, in tissue, and in applicators should be compared to those generated by other users using the identical source model. Details of the parameters used to establish these baseline single-source dose distributions should be fully documented. Any changes in these parameters, or in the computer models used to generate these baseline dose curves, must also be noted. We stress, again, the importance of the user fully understanding the computation algorithms and the parameters used.

VII. QUALITY ASSURANCE

Quality assurance procedures must be established for the equipment, e.g., the remote afterloader unit and its ancillary accessories, and for the process of using the equipment, e.g., proper execution of a planned treatment.

A. Equipment

Quality assurance tests are designed to confirm that the system (remote afterloading unit, facility, applicators, sources, etc.) performs within the tolerances established during the acceptance tests. In some cases the quality assurance test procedure is identical to the acceptance test procedure; in other cases, less rigorous quality assurance tests are performed.

AAPM Report 13, *Physical Aspects of Quality Assurance in Radiation Therapy*[64] recommends quality assurance procedures for both conventional and remote afterloaders in brachytherapy. AAPM Task Group 40 has a draft document (1992) on comprehensive quality assurance procedures that includes a chapter on quality assurance for conventional manual brachytherapy and remote afterloaders. Generally, the quality assurance procedures recommended for conventional low dose rate brachytherapy sources (sealed tubes, seeds) apply whether these sources are handled remotely or manually. However, additional quality assurance procedures are required for the remote afterloading unit. Moreover, the exact types of acceptance tests and quality assurance procedures will depend on the type of the remote afterloader system and the type of radioactive sources. We encourage readers of this report to concurrently read the report that will result from the work of Task Group 40.

Two extrinsic factors affecting the quality assurance program include the location of the remote afterloader and the workload and frequency of use of the unit. If remote afterloading units are in dedicated treatment rooms or vaults unused by other patients, equipment quality assurance is easier to perform as it generally can be done during regular work hours. If the unit is in a teletherapy vault, access for quality assurance may be limited to after hours. Moreover, if a LDR unit is in a room used by non-therapy patients, access may be very difficult as it requires "blocking" the room for periods of times so that it is not used by patients.

B. Frequency and Type Of Equipment Quality Assurance Tests

There are no legal standards established for the frequency with which quality assurance tests should be performed, other than those written in a license application. Equipment quality assurance checks should be performed at sufficient frequency to guarantee that the equipment works properly during a therapy session.

The frequency of quality assurance testing often is determined by the frequency of use of the equipment. Generally, a unit used daily should have functional tests performed daily or weekly." Verify that the console keys and lamps work; that tape or computer printer works and has adequate paper for the duration of the treatment; that the closed circuit TV and patient intercom work; that radiation monitors, door interlocks, and warning lights work; that batteries are charged; and, that the unit operates properly during a simulated or test therapy session.

Source positioning accuracy can be determined by directly viewing, by CCTV, the source moving through a transparent scaled applicator so that source position can be determined visually with millimeter accuracy (Figure 9). To confirm desired program sequence to produce a given source arrangement, test devices with multiple treatment channels (Figure 8) can be used with films to produce, by autoradiography, the planned source arrangement.

Any computer-decayed source activity should be checked against a pre-calculated decay chart to confirm the unit has decayed source activities accurately. In a facility with only a few patients a year, all quality assurance tests can be done the day prior to or on the day that the remote afterloading unit is scheduled for use rather than daily or weekly.

Should the ^{192}Ir sources in remote afterloaders be checked to confirm proper source decay? There is a short-lived ^{194}Ir isotope that could be an undesired contaminant in a ^{192}Ir source. However, a 10% uncertainty in the half-life of ^{192}Ir (73.8 ± 7.4 days) provides only a ±3% uncertainty in decayed source activity at thirty days. A 10% uncertainty in the half-life of ^{192}Ir caused by an excessive amount of ^{194}Ir in the source capsules, is highly unlikely as the manufacturers allow these sources to decay several weeks prior to shipment, to allow the ^{194}Ir to decay.

Some facilities have developed quality assurance dose rate check devices using diodes or ion-chambers at fixed distances from the source (Figure 9). A relative value of 100% activity is determined when the new source is installed, and, at each use, or weekly, the decayed source

activity is checked. These devices check for source activity, source position and timer accuracy. We recommend this good practice procedure be done at sufficient frequency to ensure proper patient care, considering the frequency of use of the afterloading unit.

Monthly or quarterly quality assurance checks generally include confirmation of timer accuracy and linearity; confirmation of source positioning; radiography of simulated (dummy) sources in conjunction with autoradiography of the active source (Figure 6); checks of operation of the unit when power or compressed air is lost; and checks of all emergency systems; careful measurement of the lengths of source guide tubes and connectors to determine critical lengths have not changed and that all connectors function; and a review of compliance with regulatory requirements, proper signs posted and instructions present; and, proper daily or weekly QA logs completed per the license.

C. Quality Assurance in the Use of Equipment

As the use of remote afterloaders involves keying into a computer treatment parameters for a planned therapy, entry errors can occur. Often, with high dose rate units, operators must treat a waiting patient as soon as possible due to the patient's medical condition, and the pressure to treat quickly can contribute to user-generated errors.

Procedures should exist to allow quick but independent confirmation by a second person of two aspects of the proposed treatment: The planned treatment parameters and the entry into the operating console of the planned treatment parameters. Errors can occur in both processes.[18,19]

Preparation and use of well-planned pre-treatment forms and check lists for each anatomic site commonly treated is recommended. **A** generic checklist could include, but would not be limited to, the following items: Have the pre-treatment, functional QA tests been done? Is the prescription (written directive) completed and signed? Has the prepared treatment plan (prescription, target volume specification, dose, dose rates, number of sources, their spatial

positions, etc.) been independently reviewed, e.g., will the planned use of the device yield the desired dose and dose distribution? Have the treatment parameters keyed by an operator into the microprocessor controlling the unit been reviewed by a second individual? Are all pre-treatment forms completed and signed prior to treatment? Do pre-treatment autoradiographs, if any, confirm the proposed treatment is correctly entered into the console?

Standard methods of treating specific anatomic sites should be adopted so that standard key entry procedures are followed. Misadministrations most likely will occur when a treatment plan requires use of non-standard parameters and someone keys in the "usual" standard parameters. We encourage users of remote afterloading units to share, in their user groups, written materials which have been prepared for the use of specific units.

Equipment quality assurance and equipment use quality assurance are both dynamic processes; procedures, once established, should be reviewed at least annually to determine if the entire QA program is effective and efficient, and if not, changes should be made to improve the program. The QA program must be well documented for license compliance.

VIII. SOURCE CALIBRATIONS

A. Source Certificates

Purchased radioactive sources are provided with a certificate that describes the source and its activity, apparent activity, or other quantity related to activity, e.g., equivalent mass of radium with a specific wall filtration. Preferably, the certificate should state the exposure rate or reference air-kerma rate, in μGy/h, in free space at a given distance in a specified geometry, or the air kerma strength, in $\mu Gy \cdot m^2/h$. Whatever concept or term used to describe the source, the user needs to confirm the stated certificate value to within its stated uncertainty. Often, the uncertainty in the absolute accuracy of source certificate's activity will be between ±5% to ±10%.

Additionally, the certificate should state if the mean activity and its uncertainty were determined by measurements of a small number of radioactive sources selected from a larger batch (a common method of assaying low activity seeds) or measurements of the activity of each source received by the user.

AAPM Report 21[62] describes levels of "traceability" of brachytherapy source calibrations relative to MST and ADCL laboratories. Direct or secondary traceability is desired.

B. Well Ionization Chamber Calibrations of Low and High Activity Sources

The sources to be calibrated in remote afterloading devices are characterized as either short or long lived radionuclides of low or high activity. Three types of re-entrant well ionization chambers exist: Conventional chambers designed for measuring the activities of quantities of radiopharmaceuticals used in nuclear medicine; brachytherapy chambers designed to measure the activities of ^{137}Cs tubes and needles, ^{192}Ir seeds and other low activity sources; and, chambers designed to measure the activities of HDR sources.

Nuclear medicine chambers are designed to assay liquid radiopharmaceuticals contained in syringes or glass vials. Calibration factors for specific radionuclides are obtained by measuring the activities of certified activities of radionuclides in 5-ml glass ampules of standard design. Generally, these calibration factors do not apply if the tested radionuclides are contained in other than a standard container. For example, assays of ^{137}Cs sealed sources using a ^{137}Cs calibration point will not be absolutely accurate because of the difference in features of the calibration ampule of ^{137}Cs and the sealed source.

Calibrations of either long or short lived low activity brachytherapy sources by well ionization chambers designed for these sources is described in AAPM Report 13, and in other articles.- Most

recently, Weaver et al.,[69] reviewed chamber calibration, energy dependence, position dependence, and response stability of well ionization chambers designed for calibration of LDR sources. The LDR sources in remote afterloading units can also be calibrated in these well ionization chambers per AAPM Report 13,[64] assuming that the well ionization chamber is calibrated for the LDR radioisotope (^{60}Co, ^{137}Cs, or ^{192}Ir). The AAPM Task Group 40 report reviews the quality assurance tests for brachytherapy source calibrators.

Well ionization chambers designed to accommodate the large currents associated with HDR sources are now available. Goetsch et al.,[70,71] report a design of a re-entrant (well-type) ionization chamber for use with ^{192}Ir HDR sources; the chamber accommodates a 10-nA current from a 370.-GBq (10.0-Ci) Ir source. The chamber is calibrated for ^{192}Ir HDR sources of specific design and encapsulation. The University of Wisconsin ADCL and K & S Associates, Inc. ADCL provide calibration, under AAPM approved protocols, of similar HDR well-type ionization chambers purchased by users for calibration of their ^{192}Ir HDR sources of identical design to the source used to calibrate the ADCL well ionization chambers.

Can conventional nuclear medicine or brachytherapy well ionization chambers be used to calibrate HDR sources? One major difference between LDR and HDR sources is the magnitude of the currents they generate in ion chambers. The HDR sources with activities as large as 740.-GBq (20.0-Ci) obviously yield much higher currents than 740.-MBq (20.0-mCi) LDR sources. The well ionization chamber electrometer current range and linearity determine if the well ionization chamber can be used with HDR sources. For example, the RADCAL Model 4050 well ionization chamber is calibrated from 4.5-fA to 225-nA and the maximum current of 225-nA is produced by a 185.-GBq (5.0-Ci) ^{99m}Tc source, yielding 4.5-nA per curie of ^{99m}Tc. Using stated calibration factors for this chamber, the maximum activity of ^{137}Cs measurable would be about 92.5-GBq (2.5Ci); for ^{60}Co the maximum activity measurable would be about 25.9-GBq (0.70-Ci); for ^{192}Ir 111-GBq (3.0-Ci) appears to be the upper limit. Hence, a careful

review of the user's manual should identify whether a particular well ionization chamber electrometer can accommodate the hi currents provided by HDR sources one needs to calibrate.

A well insert can be designed with about 2-cm diameter cylinder of lead supported and centered on the central axis by a flange of cork so that when the source probe is placed in a re-entrant axial hole in the lead, the current created in the chamber is sufficiently reduced. This method has been used at Memorial Sloan-Kettering Cancer Center for several years to measure the strength of new and old sources at source exchange and to monitor reproducibility by the ratio of the new source strength to the old source strength, corrected for radioactive decay.

C. Use and Quality Assurance of Well Ionization Chambers

Well chambers generally exhibit a strong energy dependency; any well ionization chamber needs to be calibrated for the radioisotope for which the calibration certificate value is to be measured. Nuclear medicine well ionization chambers are not likely to be calibrated for ^{192}Ir (average energy of about 0.38-MeV, poly-energetic spectrum) but will likely have a ^{198}Au calibration factor (0.412-MeV, monoenergetic). While the average energies are similar, a RADCAL Model 4050 ionization chamber has, relative to ^{226}Ra, about 10% higher response for the ^{192}Ir than for ^{198}Au (Figure 11) and the ^{198}Au calibration factor should not be used for ^{192}Ir.[69]

Source encapsulation and capsule design affect calibration. A calibration for a radioisotope is specific to the wall thickness of that capsule; the well chamber will respond differently to the same radioisotope in a different source encapsulation. Changing the thickness or material composition of the central axis insert (source holder) may also alter chamber response.

Central axis positional dependency (Figure 12) of well chambers has been reported by numerous authors.- The positional dependency also is energy dependent and must be measured for each radionuclide. Usually source holders can be designed to accurately reposition sources

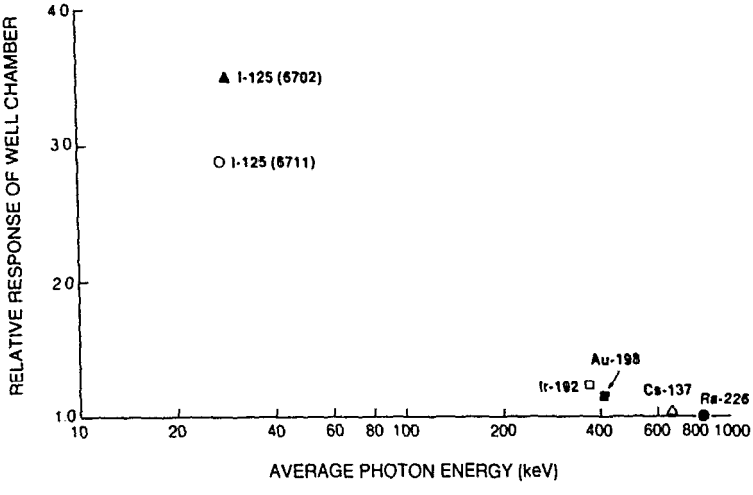


Figure 11. Energy dependence of Ar filled well ionization chamber. Responses are normalized to that of ^{226}Ra. 6702 and 6711 are model number of ^{125}I sources. (Courtesy of K. A. Weaver, San Francisco, CA).

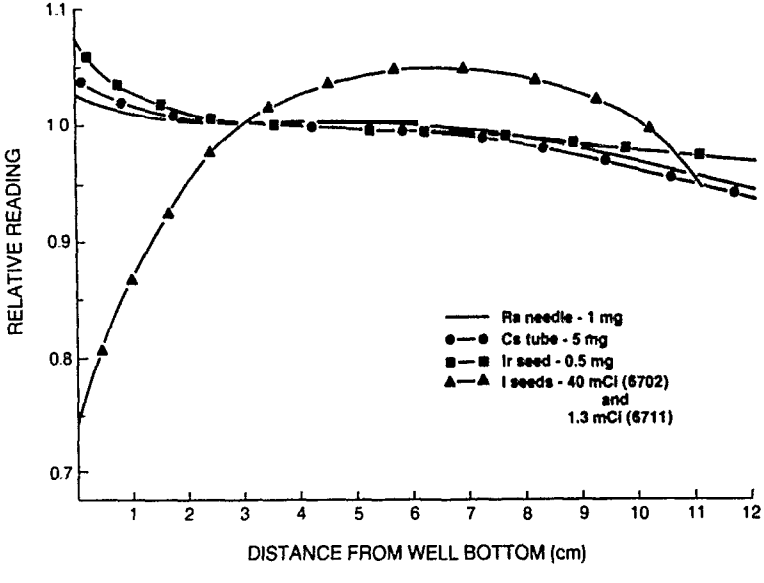


Figure 12. Variation in response of well ionization chamber with vertical position along the well axis, for several radionuclide sources. (Courtesy of K. A. Weaver, San Francisco, CA).

at specific locations along the central axis where the positional dependency is least. The well chambers designed for HDR sources exhibit a heat dependency, e.g., the 370.-GBq (10.0-Ci) sources can increase the air temperature in the collection well if they remain there for several minutes.[72] Styrofoam thermal absorbers can be positioned around the source holder to alleviate this problem.

Collection efficiency is a function of current, which is proportional to the HDR source activity. As the source activity decreases, the collection efficiency may increase slightly. As with external beam chambers, it may be necessary to measure this phenomenon by measuring current produced at multiple voltages.

As the well chambers connect to the electrometers via cables, care should be paid to leakage currents and other cable related phenomena that can affect charge or current readings.

Finally, it is important to test at frequent intervals, using a long lived radionuclide (^{137}Cs, ^{90}Sr), the constancy of the well chamber response. This may be difficult for an HDR chamber, as long-lived high activity check sources are not readily available. Consider using the highest activity ^{137}Cs or ^{60}Co sealed source one can obtain; alternately, place the well chamber in the beam of a ^{60}Co teletherapy unit and measure the current collected in a standard, reproducible geometry. A reproducibility of at least 0.5% is desired.

Well ionization chambers will respond to scatter radiation.[72] Hence, when used, they should be placed well away from walls that may scatter radiation back to the chamber. They should be used in the same location, in a constant geometry, in a reproducible manner. If moved from one location to another where the actual measurements are made, allow adequate time for the well chamber to reach equilibrium temperature with the air in the room.

D. Ionization Chamber Calibrations of LDR and HDR Sources

Source calibration techniques using NIST or ADCL calibrated

spherical or cylindrical chambers in air, water, or water equivalent media have been described for LDR remote sources by Meertens,[73] Pipman et al.,[74] for HDR sources in Gamma Med units by Bruggmoser et al.,[75] Buffa[76] and Cerra and Rodgers,[58] and HDR sources in the MicroSelectron by Ezzell[77,78] and Jones and Bidmead,[79] Jones,[53] Flynn,[80] and by Goetsch and Attix,[81] and Goetsch et al.[70] If appropriate dosimetry corrections are made, calibrations in air, water, or water equivalent media yield equivalent results.

1. Calibration Factors

Obviously ^{60}Co and ^{137}Cs LDR and HDR source(s) would be calibrated with an ion chamber and build-up cap calibrated for the particular radionuclide of the LDR or HDR sources(s). Chamber calibrations for ^{60}Co and ^{137}Cs are available from NIST and ADCL laboratories, but no such calibration is available for ^{192}Ir.

Methods of obtaining an ion chamber calibration for ^{192}Ir are under active investigation. Ezzell[77,78] obtained a ^{192}Ir calibration factor by interpolation between chamber calibration factors for ^{60}Co with its build-up cap and for superficial or orthovoltage photon energies without a cap; calibration factors were plotted against the effective energies based on the half-value layers of the photon beams and the ^{192}Ir value obtained by interpolation at 300-kV.

As a practical matter, most 250-kV x-ray chamber calibrations are usually performed without a cap; before using any existing 250-kV x-ray chamber calibration point, users should review the calibration certificate carefully to determine if the build-up cap was present or absent during calibration.

Goetsch and Attix[81] originally recommended that ionization chambers intended for use with ^{192}Ir gamma-ray sources be calibrated instead with ^{137}Cs gamma rays and moderately filtered 250-kV x radiation, and the two calibration factors be averaged. Both calibrations were performed with a chamber wall (including cap) having a minimum

thickness of 9.3×10^{22} electrons/cm^2 (e.g., 0.31-g/cm^2 graphite). The same wall (including cap) thickness must then be used for ^{192}Ir measurements. More recently, Goetsch et al.,[70] described a procedure to interpolate between, rather than average, the ^{137}Cs and 250-kV calibration points.

$$(N_x)_{Ir} = (1 + x)[(N_x)_{x\text{-}ray} + (N_x)_{Cs}]/2 \qquad [R/C] \qquad [2]$$

$$x = 0.0037\ (t/9.3 \times 10^{22}) \qquad [3]$$

where

$(N_x)_{Ir,x\text{-}ray,Cs}$ denotes the calibration factors, in roentgen per coulomb, for ^{192}Ir, 2.50-kV x-rays, and ^{137}Cs, respectively.

t denotes a wall plus cap thickness expressed in electrons/cm^2.

9.3×10^{22} is the number of electrons/cm^2 in 0.31 g/cm^2 of graphite.

0.0037 corrects for attenuation by a wall plus cap thickness of 0.31 g/cm^2.

Both University of Wisconsin ADCL and K & S Associates, Inc. ADCL use this interpolative method to obtain $(N_x)_{Ir}$ for chambers. Ezzell[82] reports a 1.2% increase in his previously reported calibration factor using Goetsch et al.[70] technique relative to the calibration factor obtained by Ezzell's method[77,78] of interpolation between a chamber factor for ^{60}Co with a cap and 250-kV without a build-up cap. This interpolative method likely will serve as the “best” method of obtaining an ^{192}Ir calibration point until NIST develops a direct method of chamber calibration with ^{192}Ir.

Users of HDR ^{192}Ir sources who desire to calibrate their sources by

thimble ionization chamber measurements may request a 250-kV calibration point and a ^{137}Cs calibration with the same cap; the wall plus cap thickness can be greater than 0.31g/cm^2 graphite, but should not be less. Since the AAPM Task Group 3 has approved this interpolative method of obtaining (NJ, we suggest users follow the identical procedure, as described by Goetsch et al.[70]

2. "In-Air" Calibrations

In-air calibrations should be done at large distances relative to the dimensions of the radioactive source(s), preferably with a spherical ionization chamber. If a cylindrical chamber is used, the long dimension of the collecting volume should be perpendicular to the longest dimension of the source(s). Source holder, ion chamber holder, and support stand should be low density plastic to minimize scattering (Figure 13). Source and chamber should be near the center of a large room and well above the floor, to minimize any contribution from room scattering. The same location in the room, with the same equipment about, should always be used for subsequent calibrations of the source or replacement sources, so that the room scattering effects, if any, are constant. Large volume ion chambers are better than the conventional 0.6-cm^3 cylindrical Farmer type chambers. Buffa[76] notes that 3-cm^3 ion chamber yields 1-pA 40-cm from a 370.-GBq (10.0-Ci) source; Ezell[78] notes that 0.6-cm^3 ion chambers can yield 5-pA at 20-cm from a 300.-GBq (8.10-Ci) source. As long integrated charge collection periods may be required, leakage charge should be measured and corrections made to the integrated charges measured. To minimize leakage, use low noise electrical cables, allow long electrometer warm-up times and keep cable lengths short to minimize the lengths of cables exposed to radiation.

Depending on ion chamber volume and collection efficiency, “in-air charge measurements may be made a few centimeters from the source and up to l-m from the source. For LDR sources the low current necessitates measurements at closer distances, which is why well ionization chamber measurements are preferred. Measurements made close to the source exhibit higher charges, shorter end-effect (timer

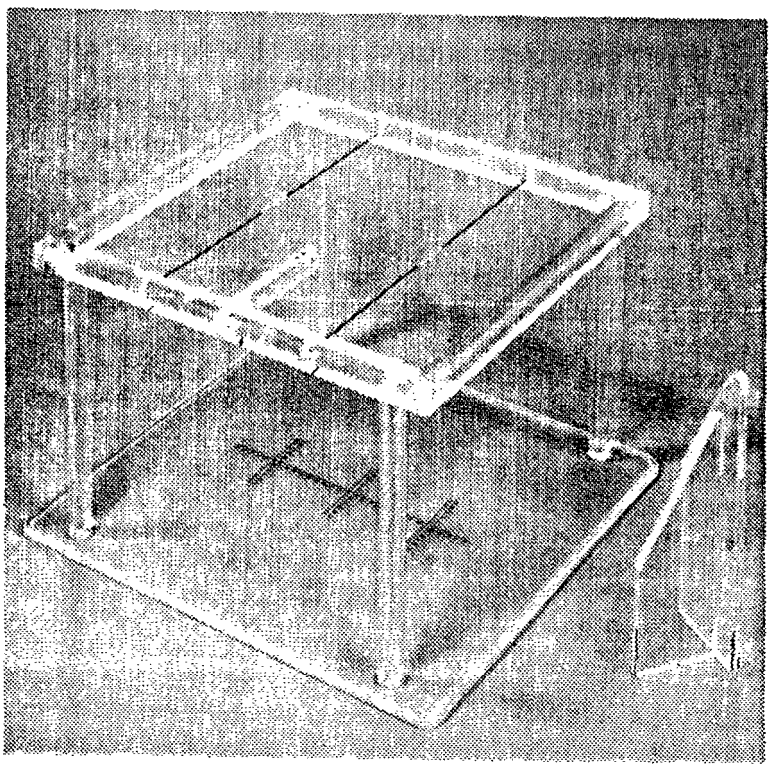


Figure 13(a). Calibration fixture designed to minimize radiation scatter. (Courtesy of Miles Mount, Nucletron Corporation, Columbia, MD.)

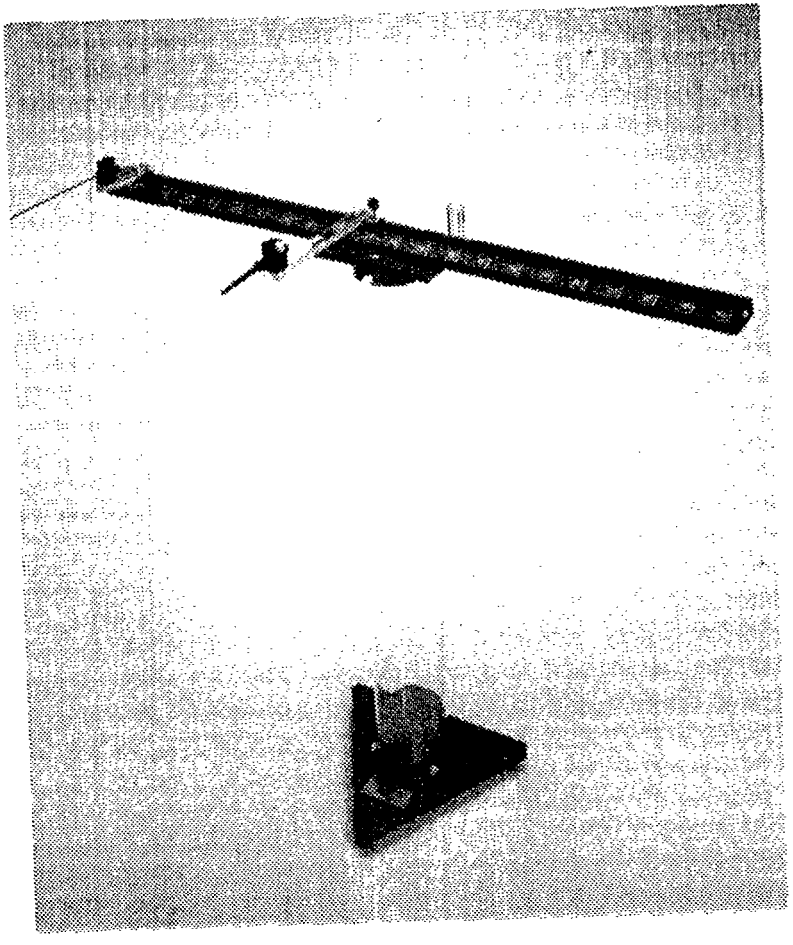


Figure 13(b). Calibration stand designed to minimize radiation scatter (Courtesy of Felix Mick, Mick Radio-Nuclear, Inc., New York, NY.)

error) corrections, which represent the charge collected during source transit, and smaller room scatter contributions, as a percentage of the measured charge. However, exposure gradient corrections necessary for the finite dimensions of the chamber volume are larger; small positional errors cause greater percentage errors in the measured charge. Conversely, at larger distances where integrated charges are markedly less, source end-effects (timer errors) are larger, and room scatter contribution represents a larger percentage of the measured charge. However, the exposure gradient corrections are much smaller and positional errors are less important. Leakage charge corrections may be larger.

The "in air" calibrations can be done by using integrated charge measured at a single distance or at multiple distances as described in (d), which follows. In addition to the conventional electrometer/chamber charge collection efficiency corrections, the single distance charge measurements may require corrections for (a) air attenuation and multiple scattering, (b) the exposure gradient across the chamber, (c) the "room scatter" effects, (e) and end-effect (timer errors).

a. In-air attenuation and multiple scattering of photons (figure 14) depend on the source to chamber distance. Most[70,71,78,79] reporting on "in air" calibrations of LDR and HDR sources neglect attenuation and multiple scattering of photons in air. Read et al.," at the National Physics Laboratory, adopted 0.2% per meter as the correction for attenuation and multiple scattering in air for ^{226}Ra, ^{60}Co, and ^{137}Cs. Hence, at distance of 5-cm to 100-cm likely to be used for in-air calibration of HDR sources, neglecting air attenuation and multiple scattering is reasonable.

b. The exposure gradient (displacement) corrections are required because of the finite dimensions of the chamber. These corrections are greatest when the dosimeter size is comparable with its distance from the source and are least when the chamber dimensions are small relative to its distance from the source. Spherical chambers exhibit

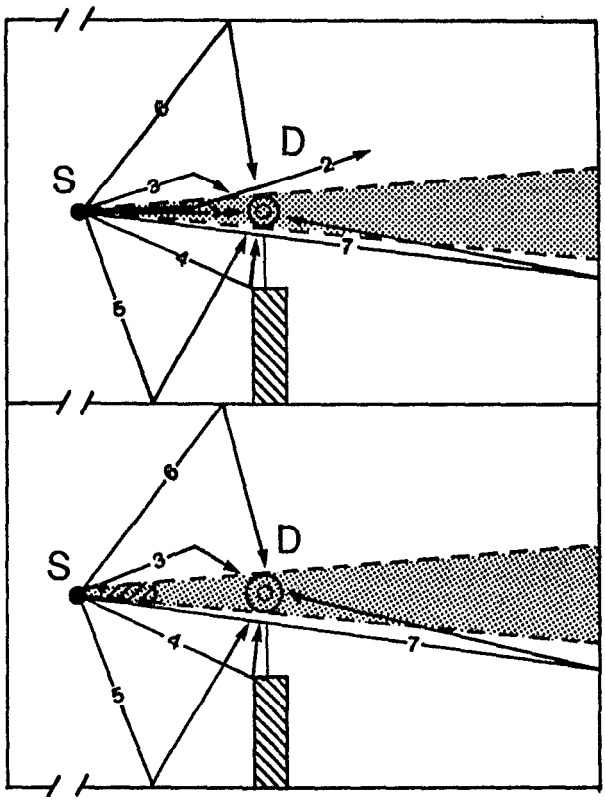


Figure 14. Radiation attenuation and scattering in a room. A source, S, is near the center of the room; detector, D, is mounted on a plastic support stand. (Top) **(1)** primary ray, (2) ray attenuated or scattered, by air, (3) ray scattered by air, toward D; (4) ray scattered by stand; (5) ray scattered by floor; (6) ray scattered by ceiling; (7) ray scattered by wall. The effects of rays (2) and (3) often are neglected. Rays 4-7 constitute room scatter radiation. (Bottom) A conical 3 TVL shield, with a cross section sufficient to shield the source, intercepts rays 1 and 2. Measurements in this geometry include room scatter contributions, rays 4-7 and the multiple scatter ray 3, from air. (Courtesy of G. P. Glasgow, Maywood, IL).

smaller displacement corrections than cylindrical chambers. Dove[84] and Kondo and Raldolph[85] provide protocols for these corrections, which can vary, from about 1.2% at 10-cm to 0.1% at 40-cm for a 0.5-cm^3 cylindrical Farmer type chamber. Bielajew[86] reviewed the theory of these corrections, extending the work of Kondo and Randolph;[85] Tolli[87] investigated the displacement effect at 20-mm source-chamber distance for ^{192}Ir, ^{60}Co, and ^{137}Cs.

For an idealized cylindrical chamber (Figure 15) with a cavity of radius, a, and length, *2h*, located a distance, *X*, from the source with its length perpendicular to *X*, Dove[84] determined that the ratio of the measured exposure rate, D(X,a,2h), to the true exposure, D(X), is given by:

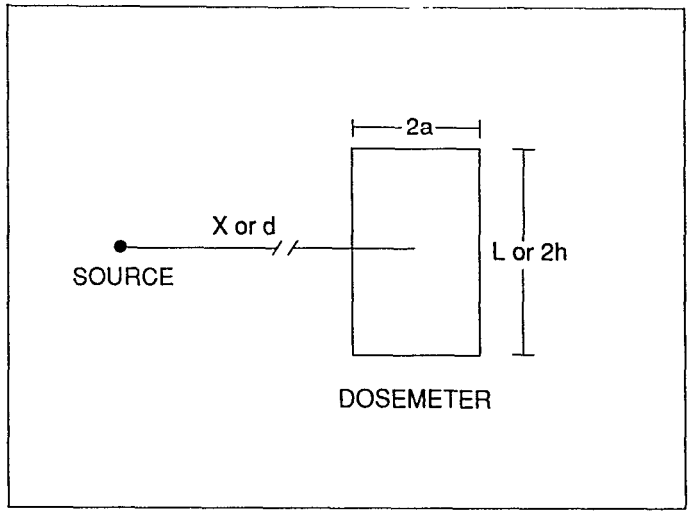


Figure 15. Source cylindrical chamber geometry for exposure gradient (displacement) corrections. The letters in lower case denote parameters used by Dove[84]; those in upper case are the parameters used by Kondo and Randolph[85]. The source-to-center of chamber distance is *X* or *d;* the chamber cavity diameter is *2a;* the chamber cavity length is *2h* or ***L.***

$$\frac{\bar{D}(X,a,2h)}{D(X)} = \left[\begin{array}{l} 1 - 1/X^2\,(h^2/3 - a^2/2) \\ + 1/X^4\,(h^4/5 - 2h^2a^2/3 + a^4/3) \\ - 1/X^6\,(h^6/7 - 7h^4a^2/20 + h^2a^4/9 - a^6/4) \end{array} \right] \quad [4]$$

where the condition

$$h^2 < X\sqrt{(2X^2 + 4a^2) - (X^2 + a^2)} \quad [5]$$

must be satisfied. Dove[84] provides illustrative examples of the correction for this geometry and additional equations for other geometries.

Kondo and Randolph[85] provide similar corrections, K, in which a distance factor, α, equal to the ratio of chamber cavity radius, a, to the distance, *d*, of the chamber's center from the source of radiation, is expressed as a function of the shape factor, σ, equal to the ratio of chamber radius, (ı, to chamber cavity length, ***L.*** K, is the ratio of the measured exposure rate to the true exposure rate, conceptually identical to Dove's correction. Table 4, a partial table, applies for cylindrical chamber positions perpendicular to the source. Kondo and Randolph[85] provide an additional table for another chamber - source geometry. For a given chamber and source geometry, Dove's[84] equation and Table 4 (an expanded version of Kondo and Randolph's Table l)[85] provide similar corrections.

c. Room scatter includes reflective contributions from all surfaces in the room, including the chamber holding stand. Often room scatter is assumed to be a constant contribution to the integrated charge, independent of the chamber to source distance. However, this is likely true only if the chamber and source are both about 2-m from scattering surfaces. Buffa[76] investigated room scatter using three-tenth value layer shield block on a mobile stand (Figure 14) and positioning the shielding block between the source and the ion chamber. The block should have a small conical cross section, and be placed as close as possible to the source, but fully shield the chamber. As the block will transmit only 0.1% of any incident radiation, measurements above that

Table 4. Values of factor K_s, the ratio of measured exposure rate to true exposure rate, for cylindrical chambers with sideward positioning of sources. *a* is cavity radius; *d* is the distance from the source to the center of the cavity; ***L is the cavity*** length.**

DISTANCE FACTOR	SHAPE FACTOR $\sigma = a/L$					
$\alpha = a/d$	0.01*	0.1*	0.15*	0.25	0.5	0.7
0	1.000	1.000	1.000†	1.000	1.000	1.000
0.005	0.927	0.9992	------	------	------	-----
0.007	0.870†	0.998†	0.9993†	------	------	------
0.01	0.785	0.997	0.9986†	0.9999	0.9999	1.000
0.03	0.416†	0.972†	0.987†	------	------	------
0.05	0.275	0.927	0.966†	0.9878	0.9980	0.9998
0.1	0.147	0.785	0.882†	0.9541	0.9921	0.9992
. . . . .						
0.5	0.0310	0.275	0.384†	0.5965	0.8630	0.9756
. . . . .						
0.9	0.0173	0.162	0.234†	0.4375	0.8497	1.0981

* Approximate value based on $K_s = \lambda^{-1} \tan^{-1} \lambda$ where $\lambda = \alpha/\sigma$.

** For complete table, see S. Kondo and M. L. Randolph, Rad Res 13, 47 (1960).

† Table entries are approximate values calculated from $\lambda^{-1} \tan^{-1} \lambda$; other entries are from the original article.

represent room scatter contribution. As room scatter may well be only 0.1% to 05% of the measured charge, depending on the room size and the source-chamber location, these shielded measurements must be done with greater care to obtain a charge signal above that contributed by leakage charge.

Ezzel[78] describes an alternate measurement of room scatter. Assuming room scatter is a constant contributor at all measurement distances, i.e., independent of the source-to-chamber distance, then

$$X = X_0 (d_0/d)^2 + X_{RS} \qquad [R] \quad [6]$$

where

d = distance from the source to the point of measurement.

d_0 = distance from the source to a reference point.

X = total exposure (primary plus room scatter) at d.

X_0 = primary exposure at d_0.

X_{RS} = room scatter exposure, assumed constant for all d.

By making measurements of equal duration at distances of 20, 30, 40, and 50-cm, regression analysis of X versus $(d_0/d)^2$ will yield X_{RS} and X_0. The measurements must be corrected for other distance dependent factors such as end-effects (timer error) and chamber gradient corrections, prior to the analysis. As the room scatter is likely less than 0.5%, very careful charge measurements are required, with proper measurements of leakage charge.

Goetsch et al.[70] expanded the method of Ezzell. They used an independent timer to trigger a pulse to an electrometer to start and stop charge integration while the source remained at the desired source-to-chamber location. In this way, they eliminated the need to

make corrections for the source transit time. For in-air measurements, the chamber response was corrected to account not only for room-scattered radiation, but also for the effective distance between source and chamber centers. These corrections were handled by considering deviations from the inverse square law (which applied only to primary photons) as the source-to-chamber distance was changed by accurately known amounts using the drive mechanism of a beam scanning system.

Following the methodology of Goetsch et a1.,[70] if the measured distance is in error by an amount, c, then

$$d' = d + c \qquad [m] \qquad [7]$$

where

d' = the effective center to center source-chamber distance.

d = the measured source-chamber distance (with an arbitrary but constant offset).

C = the correction or error in the distance.

Assuming the same amount of room scatter radiation, M_s, is included in each integrated charge reading M_d, then

$$M_d = M_d' + M, \qquad [C] \qquad [8]$$

where M_d' is the integrated charge reading due only to primary radiation.

At each nominal distance, ***d,*** a constant, f, independent of ***d,*** is:

$$f = M_d' \cdot d'^2 = (M_d - M_s) \cdot (d + c)^2 \qquad [m2 \cdot C] \qquad [9]$$

Any group of three equations, made at three or more distances, can be used to solve for the three unknowns, f, c, and M,. The quantity f is

combined with the exposure rate constant and with the chamber's exposure calibration factor to determine the source strength.

d. Calibration data at a single source-to-chamber distance may be obtained by measuring the charge rate (current) or charge collected in an interval of time.

Following the dosimetry concepts of Attix[88], the free ah exposure rate, X(r), at a distance, *r*, from the source, can be calculated from:

$$\dot{X}(r) = \dot{M}_r \cdot C_{TP} \cdot A_{ion} \cdot P_{ion} \cdot P_{grad} \cdot P_{RS} \cdot N_X \qquad [R/s] \quad [10]$$

where

$$\dot{M}(r) = \left\{ \frac{M_r}{t + \alpha} \right\} \qquad [C/s] \quad [11]$$

and

M_r = the accumulated charge, in coulombs, corrected for leakage, but not corrected for chamber dose gradient or room scatter effects.

t = the duration of charge collection in seconds.

α = the end effect (timer error) in seconds, a transit time of the source(s) and a function of *d*.

C_{TP} = the conventional temperature and pressure correction for ionization chambers.

A_{ion} = the correction for the collection efficiency of the electrometer/chamber at calibration.

P_{ion} = the correction for the collection efficiency of the electrometer/chamber at the time of the study.

P_{grad} = the exposure gradient (displacement) correction.

P_{RS} = the room scatter correction, $(X - X_{RS}/X)$.

N_x = the calibration factor for the ion chamber/electrometer at calibration conditions, in roentgens per coulomb.

From the free air exposure rate,X(r), one can then obtain the collisional air kerma rate at *r*, $K_{air}(r)$:

$$\dot{K}_{air}(r) = \dot{X}(r) \cdot (\overline{W}/e)_{air} \qquad [Gy/s] \qquad [12]$$

with X(r) in R/s in air, and $(W/e)_{air}$ in air is the mean energy expended per unit charge released in dry air; $(W/e)_{air}$ = 33.97 J/C = 87.6-Gy/R.

Although the primary goal is to measure a source strength for use in clinical dose calculations, a secondary goal is to derive a strength value that can be compared to the manufacturer's stated calibration of the source.

As the calibration certificate may state activity in megabecquerels (curies), apparent activity (in milligram radium equivalent), or, air kerma rate (μGy/h) at a reference distance, care must be exercised in making all appropriate conversions to the measured quantity for comparison to the parameter stated on the certificate. AAPM Report 21 is a useful guide.[62]

The apparent activity, A,, follows from:

$$\dot{X}(r) = (\Gamma_\delta)_X A_{APP}/r^2 \qquad [R/s] \qquad [13]$$

$$A_{APP} = \dot{X}r^2/(\Gamma_\delta)_X \qquad [Bq] \qquad [14]$$

Where $(G_d)_c$ is the exposure rate constant for an encapsulated source with a specific wall thickness. $(G_d)_c$, traditionally expressed in $R \cdot cm^2/h \cdot mCi$, must be converted to $R \cdot m^2/Bq \cdot s$, to maintain consistent nit notation in [13] and [14]. A, is the apparent activity of the source.

Alternately, the apparent activity, A_{APP}, follows from:

$$\dot{K}_{air}(r) = [A_{APP} (\Gamma_\delta)_K / r^2] \qquad [Gy/s] \qquad [15]$$

$$A_{APP} = [\dot{K}_{air}(r)\, r^2 / (\Gamma_\delta)_K] \qquad [Bq] \qquad [16]$$

where $(G_d)_c$ is the air kerma rate constant, in $Gy \cdot m^2/Bq \cdot s$, for an encapsulated source with a specific wall thickness;

$$(\Gamma_\delta)_K = (\Gamma_\delta)_X \cdot (\bar{W}/e)_{air} \qquad [Gy \cdot m^2/Bq \cdot s] \qquad [17]$$

In equations 13 - 17, one should use the manufacturer's selected values for $(G_d)_c$ or $(G_d)_K$ with careful attention to the units, as these were the values used by the manufacturer in obtaining A_{APP} for the certificate.

e. The factor M in equation 11 is the charge collected per unit time with the source at a fixed calibration distance from the chamber. M_r should not include charge collected during source transit. There are several ways to correct M_r for the transit charge.

If a timer other than that of the remote afterloader is available to start and stop charge integration while leaving the final reading frozen on the electrometer's display, integration can begin after the source has reached its calibration location and terminated before the source returns to the safe. In this case, M_r is the total charge collected divided by the total time. Goetsch et al.[70] achieved this with an electronic timer rigged to trigger a pulse to start and stop an electrometer. Care must be taken to avoid including any transient charge collection associated with the opening of the electrometer input, if that event defines the start of the time interval. A programmable electrometer, such as a Keithley Model 617, can be programmed to

record, store, and display data at predetermined time intervals. Otherwise, a stop watch may be used to measure the time between two voltages displayed by the output digital voltmeter.

If the remote afterloader timer is used (not recommended), corrections must be made for the charge collected during source transit (end effect or timer error). Ezzell[82] used standard techniques developed for shutter timing errors to measure the source transit time. The correction for transit time can be obtained from a linear regression analysis of integrated charges collected for different time intervals; M_r is the slope of the resulting line. The fractional contribution from source transit increases with source-to-chamber distance (Figure 16). Therefore, the linear regression analysis must be done for each distance. If desired, the source transit time can be obtained from the linear regression analysis on M_r obtained from Eq. 11.

Alternately, the charge collection rate, M_r, can be taken as equal to the difference between the charge collected for two timed measurements divided by the difference between the corresponding times. The subtraction of the two integrated charges removes the contribution from source transit because it is independent of time. In this case,

$$\dot{M}_r = \frac{M_r(t_2) - M_r(t_1)}{t_2 - t_1} \qquad [C/s] \qquad [18]$$

3. ***Selecting a Source Strength***

Does the measurement of apparent activity, exposure rate, or air kerma rate at a stated distance, or other derived parameter, agree with that stated on the source calibration certificate? AAPM Task Group 40 recommends that if the verification measurements disagree with the manufacturer's value by more than 3%, the disagreement should be investigated; discrepancies greater than 5% should be reported to the manufacturer. It further recommends that clinical calculations be based on the local measurement of the source strength and that discrepancies relative to the manufacturer's value serve to motivate a thorough check of the calibration procedures followed, and, if indicated, a repeat measurement.

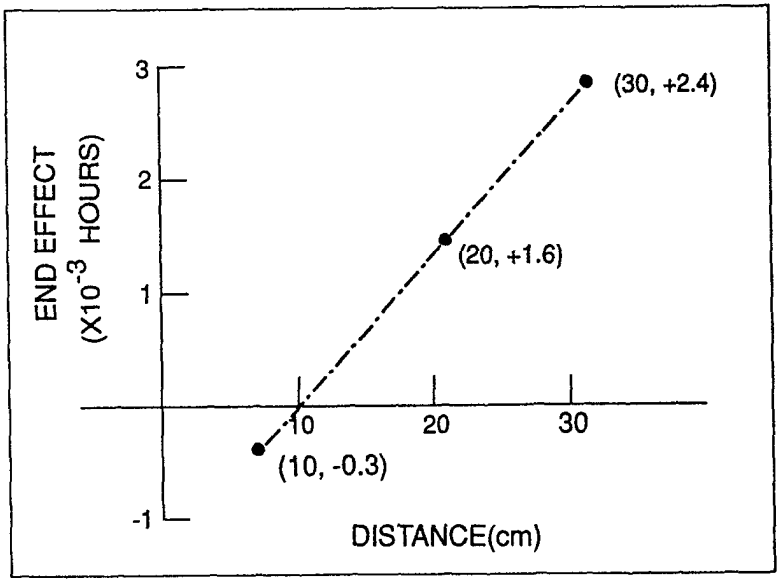


Figure 16. End effects (timer error) versus distance for a Selectron-LDR unit. Each unit will have a different timer error. (Courtesy of G. P. Glasgow, Maywood, IL).

Disagreement between numbers often is expressed by the ratio of the measured to manufacturer value. However, caution is advised, as the uncertainty in each value must be considered. For example, ^{192}Ir seed activities commonly are expressed with standard deviations as large as 7%. Similarly, a batch of ^{137}Cs pellets in an LDR remote afterloader has activities matched to within ±5% (Figure 17). Experimental measurements made of only a sample of sources from a batch must be evaluated considering the stated spread of source activities in the batch.

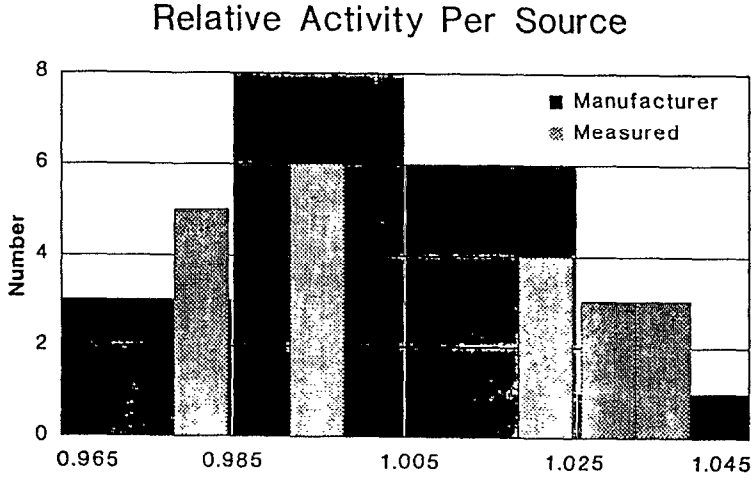


Figure 17. Relative activities of 18 ^{137}Cs pellets in a Selectron LDR. Measurements in a well ionization chamber confirmed the manufacturer's stated relative activities were within ± 5% of the mean activity of the 18 pellets. (Courtesy of G. P. Glasgow, Maywood, IL).

Unfortunately, the single ^{192}Ir high activity (370.-GBq[10.0-Ci]) sources now available usually have a source activity, or related parameter, stated to only 10% accuracy. A consistent and reproduciblc method of verification measurements is vital, and the uncertainty and reproducibility of the verification measurements should be known and considered when deciding if the verification measurement agrees or disagrees with the manufacturer's stated value. Reproducibility of in-air measurements can be established conveniently by measuring both the old and new source strength at the time of source change, or, alternately, measuring the new/old strength ratio in a well chamber prior to the in-air measurement of the new source strength.

4. The dose to a medium from the in-air calibration

The dose rate to a small mass of water in free space at ***r,*** where the radius of the water sphere is the minimum required to establish either charged particle equilibrium or transient charged particle equilibrium, is:

$$\dot{D}_{free\ space}(r) = \dot{X}(r) \cdot (\overline{W}/e)_{air} \cdot (\mu_{en}/\rho)_{air}^{water} \cdot A_{eq} \cdot \beta_{water} \quad [Gy/s] \ [19]$$

where

$(\mu_{en}/\rho)_{air}^{water}$ = the ratio of mass energy absorption coefficients;

A_{eq} = the equilibrium thickness attenuation correction for the small mass of water in free space;

β_{water} = the quotient of absorbed dose by collisional air kerma rate.

Attix[88] provides an excellent discussion with numerical examples of $(\mu_{en}/\rho)_{air}^{water}$, A_{eq}, and β_{water} for ratio and ^{137}Cs. Table 5 includes these values as well as values for ^{192}Ir as selected by TG 41.

The dose rate at a point (r, θ) in a full scattering phantom is:

$$\dot{D}_{med}(r,\theta) = \dot{D}_{free\ space}(r,\theta) \cdot F(r,\theta) \quad [Gy/s] \quad [20]$$

Table 5. Values of β_{water}, A_{eq}, and $(\mu_{en}/\rho)_{air}^{water}$ for ^{192}Ir, ^{137}Cs, and ^{60}Co*

	^{192}Ir	^{137}Cs	^{60}Co
β_{water}	1.000	1.001	1.003
A_{eq}	1.000	0.996	0.988
$(\mu_{en}/\rho)_{air}^{water}$	1.112	1.114	1.111

Note: $A_{eq} = 1 - (\bar{\mu}_{en}/\rho)_{water} \cdot (\rho t)_{water}$

*^{137}Cs and ^{60}Co data after F. H. Attix, Introduction to Radiological Physics and Radiation Dosimetry (John Wiley & Sons, New York, 1986) p. 364.

where the anisotropy factor, F(r, θ), is the ratio of the dose rate in a full scattering medium to the dose rate to an equilibrium mass of tissue located at the same point in free space. This accounts for absorption and scatter by the medium. In the terminology of Meisberger et al.,[89] the tissue attenuation factor is given by:

$$\alpha(r) = F(r,\pi/2) \qquad [21]$$

and accounts for absorption and scatter along the transverse axis.

While there are many reports of measurements of radial dose distributions for radioactive sources, the equations and parameters[89,90] in Tables 6 and 7 have been widely verified for conventional sources used in manual afterloading procedures. For conventional low activity seed sources likely to be used in remote afterloaders, $\alpha(r)$ or closely related values have been reported for ^{192}Ir seeds and ^{137}Cs seeds by Meisberger et al.[89], by Thomason and Higgins,[91] and for ^{192}Ir seeds by Meli et al.[92] and Weaver et al.[93].

Table 6. Some mathematical models accounting for attenuation and multiple scattering in a medium surrounding a radioactive source

REFERENCE	MODEL & DEFINITIONS
Meisberger et al.*	$X_W/X_A = A + Br + Cr^2 + Dr^3$ X_W = Exposure in water. X_A = Exposure in air. r = Distance (in cm) from source to point of calculation. A, B, C, D = Zero, first, second, and third order polynomial fitting coefficients.
Van Keffens and Star**	$f^2(d) = (1 + ad^2/1 + bd^2)$ d = Distance (in cm) from source to point of calculation. a, b = Second order coefficients.

* L. L. Meisberger, R. J. Keller, R. J. Shalek, Radiology 93, 953-957 (1968).

** H. J. Van Kleffens and M. W. Star, Int J Radiat Oncol Biol Phys 5, 559, (1979).

As previously discussed (Figure 10), the encapsulation of sources generally produces a dose anisotropy with reduced dose rates toward the ends of the source, relative to dose rates at the same distance on the perpendicular bisector. For ^{60}Co and ^{137}Cs sources, few recent reports of F(r, *q)* exist. Krishnaswamy[94] documented the dose anisotropy of ^{137}Cs tubes relative to ^{226}Ra tubes and Diffey and Klevenhagen[95] also reported the dose anisotropy of ^{137}Cs tubes used for manual afterloadiig. Thomason et al.[60] investigated dose distributions surrounding ^{192}Ir and ^{137}Cs seeds, and the effects of source encapsulation.[96]

Table 7. Polynomial fitting coefficients for models in Table 6.

Meisberger et al. Coefficients*					Van Kleffens & Star** Coefficients	
Isotope	A	B	C	D	a	b
	($\times 10^{0}$)	($\times 10^{-3}$)	($\times 10^{-3}$)	($\times 10^{-5}$)	($\times 10^{-3}$)	($\times 10^{-3}$)
^{198}Au	1.0306	−8.134	1.111	−15.970	----	---
^{192}Ir	1.0128	5.019	−1.178	− 2.008	----	----
^{137}Cs	1.0091	−9.015	−0.3459	− 2.817	8.3	10.8
^{226}Ra	1.0005	−4.423	−1.707	7.448	6.8	9.7
^{60}Co	0.99423	−5.318	−2.610	13.270	10.0	14.5

* L. L. Meisberger, R. J. Keller, R. J. Shalek, Radiology 93, 953-957 (1968).

** H. J. Van Kleffen and M. W. Star, Int J Radiat Oncol Biol Phys 5, 559, (1979).

For sources specifically designed for LDR and HDR remote afterloaders, values of α (r) for the spherical ^{137}Cs sources in the Selectron have been reviewed and investigated by Almond et al.[97], Siwek et al.[61] and Grigsby et al.[98], who report on applicator effects as well. Pla et al[99]) investigated dose distribution of HDR ^{60}Co pellets in Selectron applicators. Meli et al.[100] measured a(r) for a ^{192}Ir HDR source. Cerra and Rodgers[58] measured source anisotropy F(r, θ) for ^{192}Ir Gamma Med sources, including additional anisotropy introduced by certain applicators (Figure 10). Park and Almond[101] observed that the Meisberger et al.[89] coefficients were superior to the Van Kleffens and Star[90] coefficients in describing absorption and scatter along the transverse axis of a ^{192}Ir source in a Selectron HDR unit.

Since the anisotropy factor F(r, θ) is dependent on source design, users of remote afterloading units should carefully review the literature before adopting any specific set of values for calculation of dose distributions.

5. Calibrations in water or solid phantoms

Calibrations in water or in solid phantoms of water equivalent material allow potentially more reproducible measurements over time, relative to "in-air" measurements, as positioning errors may be less in a well-designed water or solid phantom than with "in-air" calibration devices. Any phantom must be sufficiently large to provide full scatter in all directions.

Meli et al.[102] investigated the dosimetry characteristics of polystyrene, solid water, and polymethylmethacrylate (PMMA) (e.g., lucite, perspex, plexiglass, acrylic) using a ^{192}Ir source. They concluded that polystyrene and solid water are equivalent to water even if a full scattering phantom is not used. However, the more dense PMMA provided more attenuation of primary radiation, which is compensated for by an increase in scatter under full scattering conditions; without a full scatter medium, PMMA is not truly water equivalent.

The free air exposure rate measured in a medium is given by [10] with P_{RS} equal to unity, i.e., no room scatter corrections are required.

The dose rate at a point (r, θ) in the medium is:

$$\dot{D}_{med}(r,\theta) = \dot{X}_{med}(r,\theta) \bullet (\overline{W}/e)_{air} \bullet (\mu_{en}/\rho)^{med}_{air} \bullet A_C \bullet \beta_{medium} \quad [Gy/s] \quad [22]$$

which is similar to Equation 19, except 4 is the displacement factor" (similar, but not identical, to the equilibrium - thickness attenuation correction A_{eq}) in the medium and the effects of attenuation and scattering in the medium, F(r, θ), are inherent in the measured data.

The free air exposure rate, X, is:

$$\dot{X}(r,\theta) = \frac{\dot{D}_{med}(r,\theta)}{f_{med} \cdot F(r,\theta)} \qquad [R/s] \qquad [23]$$

where f_{med}, the f-factor for the medium, is given by:

$$f_{med} = (\mu_{en}/\rho)^{med}_{air} \cdot (\overline{W}/e)_{air} \qquad [Gy/R] \qquad [24]$$

Ezzell[78] notes that in-air and in-phantom calibrations have agreed to within 2% for ^{192}Ir sources when all correction factors are applied carefully.

IX. ISODOSE COMPUTATIONS

Accurate dose computations for LDR, MDR, and HDR remote afterloading sources in an applicator, in a patient, depend on a knowledge of the dosimetry of the sources, the calibration of the sources, the relative spatial position of the sources, perturbing effects of adjacent sources and of the applicator, and attenuation and multiple scattering in tissue surrounding the source and applicator, all of which have previously been discussed. The accuracy of computer dose calculations was addressed in an earlier section.

Generally, the sources are: (1) A single source which steps through a preselected positional sequence with different dwell times at each location; (2) a single source that oscillates in a pre-determined pattern to yield the desired dose location; (3) the active source pellets that are interspaced with inactive pellets in a static linear array.

Some vendors provide precalculated isodose atlases that provide dose distributions for standard source arrangements and treatment times. While these atlases are useful, the user must clearly understand their assumptions so that corrections made and included in these dose distributions are not made a second time by the user. Such atlases generally assign a reference activity for the sources and the user must

normalize the precalculated dose distributions to the activity or calibration of the source(s) used at the time of treatment (unless such normalization is automatically performed by the machines).

Conventional radiotherapy planning (RTP) computer software often can be used to calculate the dose distributions of remote afterloader sources. It is imperative that the user understand the algorithms and various input parameters and factors the RTP computer uses for the dose calculations.

For example, while representation of a small linear high activity source as a point source is common practice, one prefers the computer algorithms to correctly represent the anistropy of the source, If the anisotropy of the source capsule cannot be modeled by the RTP computer, the user must understand how the calculated dose distribution for the point ***source*** differs from the true dose distribution around the source.

In arrays of sources, the attenuation and scattering of the adjacent active source pellets or inactive spacers should be represented,[99] but this may be difficult using conventional RTP software. Dedicated software provided by the vendor may offer a better representation of single source or multiple source dosimetry than the conventional RTP software used to represent seed and linear sources, as one presumes the vendors best know their own sources and how to represent them. However, conventional RTP computer vendors are now including special algorithms in upgrades to their software to represent remote afterloading sources.

Attenuation of applicators used for the Selectron,[98,99] the Gamma Med IIi,[58] and the Selectron HDR[50] have been reported. Computer generated isodose curves should clearly state if applicator effects have been included or neglected in the computation.

Tissue attenuation and multiple scattering, either $\alpha(r)$ or $F(r, \theta)$, often are options in isodose curve computation, with several recipes available. As previously discussed, the user should have investigated the various models available and adopt one best suited for the source design used.

Many remote afterloading sources are not static; they can move and the combination of possible multiple source positions and different dwell times at these positions, occuring in numerous catheters in a patient, is a formidable isodose computation problem, particularly for planning calculations. Dose optimization software using non-linear regression analysis techniques limited by stated boundary conditions affords one solution to this problem.

Anderson[103] describes a non-linear regression approach to calculating the dose for a ^{192}Ir source that steps along a single channel applicator. Such non-linear regression optimization methods now are available on most computer systems supplied with remote afterloading devices.

REFERENCES

1. P. R. Almond, ***"Remote Afterloading"*** in AAPM Monograph No. 9, Advances in Radiation Therapy Treatment Planning; edited by A. E. Wright and A. L. Boyer (American Institute of Physics, New York, 1983) 601-619.

2. R. F. Mould, ed., Brachytherapy 1984: Proceedings of the Third International Selectron Users Meeting (Nucletron Trading BV, Leersum, The Netherlands, 1985).

3. R. F. Mould, eds, Brachytherapy 2: Proceedings of the 5th International Selectron Users' Meeting (Nucletron International BV, Leersum, The Netherlands, 1989).

4. Proceedings of the First Symposium on Gamma Med Remote Afterloading (Mick Radio-Nuclear Instruments, Inc., New York, 1985).

5. S. M. Shah, ed.,Proceedings of the First International Meeting of Gamma Med Users (Mick Radio-Nuclear Instruments, Inc., New York, 1986).

6. Proceedings of the Second Annual International High Dose Rate Remote Afterloading Symposium, (Robert F. O'Conner, South China, ME, 1987).

7. A. A. Martinez, C. G. Orton, R. F. Mould, (eds.), Brachytherapy HDR and LDR: Proceedings of Remote Afterloading: State of the Art Conference (Nucletron Corporation, Columbia, MD, 1990).

8. P. N. K. Leung, "Experience with Remote Afterloading Technique in Intracavity Therapy", Int J Radiat Oncol Biol Phys 10, l57-162 (1984).

9. P. W. Grigsby, C. A. Perez, J. Eichling et al., *"Reduction in Radiation Exposure To Nursing Personnel With the Use of Remote Afterloading Brachytherapy Devices",* Int J Radiat Oncol Biol Phys 20, 627-629, 1991.

10. United States Nuclear Regulatory Commission Code of Federal Regulations, Title 10, Chapter 1, Part 35.20 (October 31, 1986).

11. C. Constantinou, *"Investigations and Reporting of Incidents and Accidents in Radiotherapy",* in American Association of Physicists in Medicine Proceeding No. 4, Radiotherapy Safety, edited by B. Thomadsen (American Institute of Physics, New York, 1982) 23-31.

12. L. N. Sedham and M. I. Yanni, *"Radiation Therapy and Nurses' Fears of Radiation Exposure",* Cancer Nursing 8, 129 (1985).

13. C. A. F. Joslin, *"High Dose Rate Gynecological Afterloading"* in Institute of Physical Sciences in Medicine Report 45, Dosimetry and Clinical Uses of Afterloading Systems, edited by A.R. Alderson (Institute of Physical Sciences in Medicine, London, 1986) 9-11.

14. C. A. F. Joslin, *"High Activity Source Afterloading in Gynecologic Cancer and its Future Prospects",* Endocurietherapy/Hyperthermia Oncology 5, 69-81 (1989).

15. M. Busch and W. Alberti, (eds.) High Dose Rate Afterloading Therapy of Uterine Cancer (Radiologisches Zentrum, Universitatsklinikum Essen, Essen, FRG, 1985).

16. J. F. Utley, C. F. Von Essen, R. A. Horn, J. H. Moeller, *"High Dose Rate Afterloading Brachytherapy in Carcinoma of the Uterine Cervix",* Int J Radiat Oncol Biol Phys 10, 2259-2263 (1984).

17. U. Schulz, M. Busch, U. Bormann, *"Interstitial High Dose Rate Brachytherapy: Principles, Practice and First Clinical Experiences with a New Remote Controlled Afterloading System Using ^{192}Ir"*, Int J Radiat Oncol Biol Phys 10, 915-920 (1984).

18. Report to Congress on Abnormal Occurrences. NUREG 0090, Vol. 13., No: 1, Jan. - Mar., 1990, 5 - 8.

19. B. R. Thomadsen, S. Shahabi, D. A. Buchler, M. P. Mehta, B. R. Paliwal, *"Anatomy of Two High Dose Rate Misadministrations"*, Med Phys 18, 645 (1991) (Abstract).

20. W. K. Jones, "An Unusual Afterloading Malfunction with a Curietron", Assoc Med Phys India Bulletin 10, 212 (1985).

21. R. D. Young *"Safety Considerations For Remote Afterloaders"*, Med Phys 16, 495 (1989) (Abstract).

22. C.A.F. Joslin, C.W. Smith, and A. Mallik, *"The Treatment of Cervix Cancer using High Activity ^{60}Co Sources"*. Brit J Rad 45. 257-270 (1972).

23. H. Newman, K.W. James, and C.W. Smith, *"Treatment of Cancer of the Cervix with a High Dose Rate Afterloading Machine (The Cathetron)"*, Int J Radiat Oncol Biol Phys 9, 931-937 (1983).

24. Y. Shigematsu, K. Nishiyama, N. Masaki, T. Inoue, Y. Miyata, H. Ikeda, S. Ozeki, Y. Kawamura, and K. Kurachi, "Treatment of Carcinoma of the Uterine Cervix by Remotely Controlled Afterloading Intracavitary Radiotherapy with High-Dose Rate: A Comparative Study with a Low-Dose Rate System". Int J Radiat Oncol Biol Phys 9, 351-356 (1983).

25. L. Mandell, D. Nori, L. Anderson, and B. Hilaris, *"Postoperative Vaginal Radiation in Endometrial Cancer Using a Remote Afterloading Technique"*, Int J Radiat Oncol Biol Phys 11, 473-478 (1985).

26. T. Teshima, M. Chatani, K. Hata and T. Inoue, *"High Dose Rate Intracavitary Therapy for Carcinoma of the Uterine Cervix: I. General Figures of Survival and Complication",* Int J Radiat Oncol Biol Phys 13, 1035-1041 (1987).

27. Y. Akine, H. Arimoto, T. Ogino, Y. Kajiura, I. Tsukiyama, S. Egwa, T. Yamada, K. Tanemura, R. Tsunematsu, K. Ohmi, T. Sonoda, and T. Kasamatsu, *"High-Dose Rate Intracavitary Irradiation in The Treatment of Carcinoma of The Uterine Cervix Early Experience with 84 Patients",* Int J Radiat Oncol Biol Phys 14, 893-898 (1988).

28. T. Teshima, M. Chatani, K. Hata, and T. Inoue, *"High Dose Rate Intracavitary Therapy for Carcinoma of the Uterine Cervix: II. Risk Factors for Rectal Complications".* Int J Radiat Oncol Biol Phys 14, 281-286 (1988).

29. C. Shu-Mo, W. Xiang-E., and W. Qi, *"High Dose-Rate Afterloading in The Treatment of Cervical Cancer of The Uterus",* Int J Radiat Biol Oncol Phys 16, 335-338 (1989).

30. R.G. Dale, *"The Use of Small Fraction Numbers in High-Dose Rate Gynecological Afterloading: Some Radiobiological Considerations",* Brit J Radio1 63, 290-294 (1990).

31. K.K. Fu and T.L. Phillips, *"High-Dose-Rate versus Low-Dose Rate Intracavitary Brachytherapy for Carcinoma of the Cervix",* Int J Radiat Oncol Biol Phys, 19, 791-796 (1990).

32. C.A.F. Joslin, *"Brachytherapy: A Clinical Dilemma",* Int J Radiat Biol Oncol Phys 19, 801-802 (1990).

33. W. E. Livevsage, “Dose Rate Effects”, in Institute of Physical Sciences in Medicine Report 45, Dosimetry and Clinical Use of Remote Afterloading Systems, ed. A. R. Alderson, (Institute of Physical Sciences in Medicine, London, 1986) l-8.

34. International Commission on Radiation Units and Measurements Report 38, Dose and Volume Specifications for Reporting Intracavitary Therapy in Gynecology (International Commission on Radiation Units and Measurements. Bethesda, MD, 1985) 5.

35. G. P. Glasgow, *"An Inventory of Cesium-137 Seeds for Multiple Site Interstitial Brachytherapy with a MicroSelectron"*, Endocurietherapy/Hyperthermia Oncology 5, 175-179 (1989).

36. D. J. Brenner and E. J. Hall, *"Conditions For The Equivalent of Continuous To Pulsed Low Dose Rate Brachytherapy"*, Int J Radiat Oncol Biol Phys 20, 181-190 (1991).

37. K. R. Das, A. Shanta, N. Kulkarnic, P. K. Shah, *"Ralston 20B: A High Dose Rate Remote Controlled Afterloader for Brachytherapy"*, Endocurietherapy/Hyperthermia Oncology 3, 81-89 (1987).

38. K. C. Kam and P. Dunn, *"First Year Experience with the High Dose Rate Buchler Afterloading Unit"*, in Institute of Physical Science in Medicine Report 45, Dosimetry and Clinical Uses of Afterloading System, edited by A. R. Alderson (Institute of Physical Sciences in Medicine, London, 1986) 46-59.

39. C. H. Jones and A. M. Bidmead, *"Calibration of the MicroSelectron HDR System"*, in Brachytherapy 2: Proceedings of the 5th International Selectron Users Meeting, edited by R. Mould (Nucletron International BV, Leersum, The Netherlands, 1989) 75-82.

40. C. F. Mesina, G. A. Ezzell, J. M. Campbell, C. G. Orton, *"Acceptance Testing of the Selectron High Dose Rate Remote Afterloading Cobalt-60 Unit"*, Endocurietherapy/Hyperthermia Oncology 4, 253-256 (1988).

41. A. Buffa, ***"Gamma Med II Source Calibration Employing Ionometric Techniques",*** in Proceedings of Second Annual International High Dose Rate Remote Afterloading Symposium (Health Physics Consultants, South China, Maine, 1987) 75-81.

42. National Council on Radiation Protection and Measurements Report 91. ***"Recommendations on Limits for Exposure to Ionizing Radiation"*** (National Council on Radiation Protection and Measurements, Bethesda, MD, 1987).

43. International Commission on Radiological Protection Publication 60. *"1990 Recommendation of the International Commission on Radiological Protection"* (Annals ICRP 21, 1991).

44. United States Nuclear Regulatory Commission, 10 CFR 20.1301, (a) (1) (Federal Register 56, No. 98, Tuesday, May 21, 1991)

45. J. D. Bourland, M. A. Varia, G. W. Sherouse, P. E. Stancil, L. D. Stanley, E. L. Chaney, H. L. McMurray, J. E. Tepper, *"Incorporation of Emerging Technology into the Design of a Radiation Oncology Facility: Problems Encountered"*, Phys Med Biol 33, Supp 1, 55 (1988) (Abstract).

46. A. L. McKenzie, J. E. Shaw, S. K. Stephenson, P. C. R. Turner (eds.), Institute of Physical Sciences in Medicine Report 46, *"Radiation Protection in Radiotherapy"* (Institute of Physical Science in Medicine, London, 1986).

47. E. E. Klein, P. W. Grigsby, J. F. Williamson, A. S. Meigooni, *"Pre-installation Empirical Testing of Room Shielding For HDR Remote Afterloaders"*, Med Phys 18, 655 (1991) (Abstract).

48. P. W. Grigsby and C. A. Perez, *"The Cost of Low Dose Rate Remote Afterloading Compared to Manual Afterloading Brachytherapy"*, Administrative Radiol 9, 61-69 (1990).

49. IEC, Particular Requirements for the Safety of Remote Controlled, Automatically Driven Gamma Ray Afterloading Equipment, International Standard IEC, 601, 2/17/89, Medical Electrical Equipment Part 2 (Bureau de la Commission Electrotechnique International: Geneva, 1989).

50. L. F. Mesina, G. A. Ezzell, J. M. Campbell, C. G. Orton, "Acceptance Testing of the Selectron High Dose Rate Remote Afterloading Cobalt-40 Unit", Endocurietherapy/Hyperthermia Oncology& 253-256 (1988).

51. P. W. Grigsby, *"Quality Assurance of Remote Afterloading Equipment at the Mallinckrodt Institute of Radiology",* Selectron Brachytherapy Journal 1, 15 (1989).

52. A. Flynn, *"Quality Assurance Checks on a MicroSelectron - HDR,"* Selectron Brachytherapy Journal 4, 112-115 (1990).

53. C. H. Jones, *"Quality Assurance in Brachytherapy Using the SelectronLDR/ MDR and MicroSelectron-HDR",* Selectron Brachytherapy Journal 4, 48-52 (1990).

54. E. D. Slessinger, *"A Quality Assurance Program for Low Dose Rate Remote Afterloading Devices",* in Brachytherapy - HDR and LDR, edited by A. A. Martinez, C. G. Orton, R. F. Mould (Nucletron Corp., Columbia, MD, 1990) 160-168.

55. G. A. Ezell, *"Acceptance Testing and Quality Assurance of High Dose Rate Remote Afterloading Systems",* in Brachytherapy HDR and LDR, edited by A. A. Martinez, C. G. Orton, R. F. Mould, (Nucletron Corp., Columbia, MD, 1990) 138-159.

56. E. D. Slessinger, *"Selectron - LDR Quality Assurance",* Selectron Brachytherapy Journal 4, 36-40 (1990).

57. C. H. Jones, *"Quality Assurance in Brachytherapy",* Med Phys World 6, 4 (1990).

58. F. Cerra and J. F. Rodgers, *"Dose Distribution Anisotropy of the Gamma Med II Brachytherapy Source",* Endocurietherapy/Hyperthermia Oncology 6, 71-80 (1990).

59. C. C. Ling, Z. C. Gromadzky, S. N. Rustgi, J. H. Cundiff, *"Directional Dependence* of *Radiation Fluence from 192-Ir and 198-Au Sources".* Radiology 147, 791-792 (1983).

60. C. Thomason, T. R. Mackie, M. J. Lindstrom, P. D. Higgins, *"The Dose Distribution Surrounding Ir-192 and Cs-137 Seed Sources".* Phys Med Biol 36, 475-493 (1991).

61. R. A. Siwek, P. F. O'Brien, P. M. K. Leung, *"Shielding Effects of Selectron Applicators and Pellets on Isodose Distributions",* Radiotherapy and Oncol 20, 132-138 (1991).

62. American Association of Physicists in Medicine, AAPM Report No. 21, *"Specification of Brachytherapy Source Strength"* (American Institute of Physics, New York, 1987).

63. S. Jayaraman and L. H. Lanzl, *"An Overview of Errors in Line Source Dosimetry for Gamma-ray Brachytherapy",* Med Phys 10, 871-875 (1983).

64. American Association of Physicists in Medicine Report No. 13, *"Physical Aspects of Quality Assurance in Radiation Therapy",* G. K. Svenson, Chairman (American Institute of Physics, New York, 1984) 40-43.

65. L. N. Berkley, W. F. Hanson, R. J. Shalek, *"Discussion of the Characteristics of the Results of Measurements with a Portable Well Ionization Chamber for Calibration of Brachytherapy Sources",* in Recent Advances in Brachytherapy Physics, edited by D. A. Shearer (American Institute of Physics, New York, 1981) 38-48.

66. A. L. Boyer, P. D. Cobb, K. R. Kase, and D. J. S. Chen, *"192Ir Hospital Calibration Procedures"*, in Recent Advances In Brachytherapy Physics, edited by D. A. Shearer (American Institute of Physics, New York, 1981) 82-103.

67. J. F. Willamson, R. L. Morin, F. M. Khan, *"Dose Calibrator Response to Brachytherapy Sources: A Monte Carlo and Analytic Evaluation"*, Med Phys 10, 135-140 (1983).

68. A. Niroomand-Rad, *"Routine Calibrations of Brachytherapy Sources with a Well-Type Dose Calibrator Using Standard Calibrated Sources"*, Radiat Med 8, 238-245, (1990).

69. K. A. Weaver, L. L. Anderson, J. A. Meli, *"Source Calibration"* in Interstitial Brachytherapy, Interstitial Collaborative Working Group (Raven Press, New York, 1990) 15-19.

70. S. J. Goetsch, F. H. Attix, D. W. Pearson, B. R. Thomadsen, *"Calibration of ^{192}Ir High Dose Rate Afterloading Systems"*. Med Phys 18, 462-467 (1991).

71. S. J. Goetsch, F. H. Attix, L. A. DeWerd and B. R. Thomadsen, *"A New Re-Entrant Ionization Chamber for the Calibration of Ir-192 HDR Sources"*. Int J Radiat Oncol Biol Phys 24, 167-170 (1992).

72. M. B. Podgorsk, L. A. DeWerd, B. R. Thomadsen, and B. R. Paliwal, *"Thermal and Scatter Effects on the Radiation Sensitivity of Well Chambers Used for High Dose Rate Ir-192 Calibrations"*. Med Phys 19, 1311- l314 (1992).

73. H. Meertens, *"A Calibration Method for Selectron LDR Sources"*, in Brachytherapy - 1984, Nucletron Trading BV, Leersum, the Netherlands, edited by R. F. Mould, (Nucletron Trading BV, Leersum, the Netherlands, 1984) 58-67.

74. Y. Pipman, A. Jamshidi, A. Sabbas, *"Commissioning of a Selectron LDR Remote Afterloader Tests and Measurements",* Med Phys 16, 494 (1989) (Abstract).

75. G. Bruggmoser, K. KuphaI, U. Freund, M. Wannenmacher, *"Dosimetry of the Afterloading Therapy with Gamma Med",* in Proceedings of the First International Meeting of Gamma Med Users, edited by S. M. Shah (Mick Radio-Nuclear Instruments, Inc., New York, NY, 1986) 154-159.

76. A. Buffa, *"Gamma Med II Source Calibration Employing Ionometric Techniques",* in Proceedings Second Annual International High Dose Rate Remote Afterloading Symposium (Health Physics Consultants, South China, ME, 1987) 77-81.

77. *G.* A. Ezzell, *"Evaluation of Calibration Techniques for the MicroSelectron HDR",* in Brachytherapy 2: Proceedings of the 5th International Selectron User's Meeting, edited by R. F. Mould (Nucletron International BV, Leersum, The Netherlands, 1989) 61-69.

78. G. A. Ezzell, *"Evaluation of Calibration Techniques for a High Dose Rate Remote Afterloading Iridium-192 Source",* Endocurietherapy/Hyperthermia Oncology 6, 101-106 (1990).

79. C. H. Jones and A. M. Bidmead, *"Calibration of the MicroSelectron HDR System",* in Brachytherapy 2, edited by R. F. Mould, (Nucletron International BV, Leersum, the Netherlands, 1989) 75-82.

80. A. Flynn, *"Quality Assurance Checks on a MicroSelectron HDR".* Selectron Brachytherapy JournaI 4, 112-115 (1990).

81. S. J. Goetsch and F. H. Attix, *"^{192}Ir Remote Afterloading Source Calibration",* AAPM Newsletter 15, No. 1, 3 (1990).

82. G. A. Ezzell, *"The Effect of Alternative Calibration Procedure using the NFL 2505/3 Ionization Chamber: A Brief Communication"*, Selectron Brachytherapy Journal 5, 42-43 (1991).

83. L. R. Read, J. E. Bums, R. A. C. Liquorish, *"Exposure Rate Calibration of Small Radioactive Sources of ^{60}Co, ^{226}Ra, and ^{137}Cs"*, Int J Appl Radiat Isot 29, 21-27 (1978).

84. D. B. Dove, *"Effect of Dosemeter Size on Measurements Close to a Radioactive Source"*, Brit J Radiol 62, 202-204 (1959).

85. V. S. Kondo and M. L. Randolph, *"Effect of Finite Size of Ionization Chambers on Measurements of Small Photon Sources"*, Radiation Research 13, 37-60 (1960).

86. A. F. Bielajew, *"An Analytic Theory of the Point-source Non-uniformity Correction Factor for Thick-walled Ionization Chambers in Photon Beams"*, Phys Med Biol 35, 517-538 (1990).

87. H. Tolli, *"Ionization Chamber Dosimetry: Procedure For Brachy-Beam Dosimetry and Displacement Effects in Photon Beams"*. Thesis, University of Gothenburg, Sweden, 1991.

88. F. H. Attix, *"Introduction To Radiological Physics and Radiation Dosimetry"* (John Wiley & Sons, New York, 1986) 346-394.

89. L. L. Meisberger, R. J. Keller, R. J. Shalek, *"Effective Attenuation in Water of the Gamma Rays* of *Gold 198, Iridium 192, Cesium 137, Radium 226, and Cobalt 60"*, Radiology 93, 953-957 (1968).

90. H. J. Van Kleffens and W. M. Star, *"Application* of *Stereo X-Ray Photogrammetry (SRM) in the Determination of Absorbed Dose Values during Intracavitary Radiation Therapy"*, Int J Radiat Oncol Biol Phys 5, 559 (1979).

91. C. Thomason and P. Higgins, *"Radial Dose Distribution of ^{192}Ir and ^{137}Cs Seed Sources",* Med Phys 16, 254-257 (1989).

92. J. A. Meli, A. S. Meigonni, R. Nath, *"Comments on Radial Dose Distribution* of *Ir-192 and Cs-137 Seed Sources",* Med Phys 16, 824 (1989).

93. K. A. Weaver, V. Smith, D. Huang, C. Barnett, M. C. Schell, C. Ling, *"Dose Parameters of I-125 and Ir-192 Seed Sources",* Med Phys 16, 636-643 (1989).

94. V. Krishnaswamy, *"Dose Distribution about ^{137}Cs Sources in Tissue",* Radiology 105, 181 (1972).

95. B. L. Diffey and S. C. Klevenhagen, *"An Experimental and Calculated Dose Distribution in Water around CDC-K type Cesium-137 Sources",* Phys Med Biol 20, 446 (1975).

96. C. Thomason, T. R. Mackie, M. J. Lindstrom, *"Effect of Source Encapsulation in the Energy Spectra of Ir-192 and Cs-137 Seed Sources",* Phys Med Biol 36, 495-505 (1991).

97. P. R. Almond, J. R. Marbach, P. M. Stafford, *"Brachytherapy Buildup Factors for Cesium-137 Rays",* Endocurietherapy/Hyperthermia Oncology 5, 49-52 (1989).

98. P. W. Grigsby, J. F. Williamson, C. A. Perez, *"Source Configurations and Dose Rates For The Selectron Afterloading Equipment For Gynecologic Applicators",* Int J Radiat Oncol Biol Phys 24, 321-327 (1992).

99. C. Pla, M. D. Evans, E. B. Podgorsak, *"Dose Distribution Around Selectron Applicators",* Int J Radiat Oncol Biol Phys 13, 1761-1766 (1987).

100. J. A. Meli, L. L. Anderson, K. A. Weaver, *"Dose Distribution"*, in Interstitial Brachytherapy, Interstitial Collaborative Working Group (Raven Press, New York, 1990) 21-31.

101. H. C. Park and P. R. Almond, *"Evaluation of the Build-up Effect of an ^{192}Ir High Dose Rate Brachytherapy Source"*, Med Phys 19, 1293-1297 (1992).

102. J. A. Meli, A. S. Meigooni, R. Nath, *"On the Choice of Phantom Material for ^{192}Ir Sources"*, Int J Radiat Oncol Biol Phys 14, 587-593 (1988).

103. L. L. Anderson, *"Remote Afterloading in Cancer Management: Part I: Afterloader Design and Optimization Potential", in* Brachytherapy Oncology - 1983, edited by B. S. Hilaris, M. A. Batata (Memorial Sloan - Kettering Cancer Center, New York, 1983) 93-100.